SIMULATION OF A HOT-AIR RESIDENTIAL
SOLAR HEATING SYSTEM WITH PEBBLE
BED STORAGE

Robert G. Ramsay

SIMULATION OF A HOT-AIR RESIDENTIAL
SOLAR HEATING SYSTEM WITH PEBBLE BED STORAGE

by

ROBERT G. RAMSAY
Lieutenant, United States Coast Guard

B.S.M.E. University of Rhode Island
(1969)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF

OCEAN ENGINEER
AND THE DEGREE OF
MASTER OF SCIENCE

in

MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY 1977

ACKNOWLEDGMENTS

I wish to thank Assistant Professor James D. Felske of the Mechanical Engineering Department of MIT for his patience and assistance in this work.

Additional gratitude is extended to Miss Cheryl Gibson for providing the invaluable professional skills necessary for the proper presentation of the finished work.

Further appreciation is extended to my wife, Susan, who aided immeasurably by adamantly refusing to type and to our daughter, Heather, whose inability to remain quiet I have long ago forgiven.

I also acknowledge the monetary assistance of the R & D Divison of the U.S. Coast Guard.

SIMULATION OF A HOT-AIR RESIDENTIAL SOLAR HEATING
SYSTEM WITH PEBBLE BED STORAGE

by

ROBERT G. RAMSAY

Submitted to the Department of Mechanical Engineering on
12 May 1977 in partial fulfillment of the requirements for
the degrees of Ocean Engineer and Master of Science in
Mechanical Engineering.

ABSTRACT

Water-type solar heating systems have received much
attention in the literature and several good computer simulation
models are available. Air-type space heating units have
advantages which may make them more suited to a particular
need than the water-type system.

This computer simulation offers a model of an air-type
solar heating system with which one can determine the monthly
system output. All significant system parameters are easily
varied as is the storage bed size and material. The simulation
accepts all air-type collector designs. The residence is
simply modeled and estimating its heat load is reduced to
calculating the product of floor area times a constant.
Insolation data input is based on monthly averaging-techniques.

The quantities varied in the present application of the
model were collector size and storage volume.

Thesis Supervisor: James D. Felske
          Title: Assistant Professor, Mechanical Engineering

TABLE OF CONTENTS

Page

TABLE OF FIGURES AND TABLES

NOMENCLATURE

Numbers in ( ) refer to the equation(s) in which the symbol appears.

A (12,14,15)	cross-sectional area of pebble bed storage unit m^2
A_c	overall collector area m^2
A_p (13)	total surface area of pebble bed storage unit m^2
A_{xs} (9)	area of collector normal to air flow m^2
b	subscript refering to the storage bed material
c_b (13,15)	specific heat of pebbles in storage bed; assumed constant at 0.837 KJ/Kg - °C
c_f (11-13,15)	specific heat of air; assumed constant at 1.012 KJ/Kg - °C
D (14)	diameter of pebbles, all assumed equal m
D_H (7,9)	characteristic length of collector (hydraulic diameter) for use in determining Reynold's number; equal to twice the spacing between the plates m
d (23)	dust factor
F' (11)	collector efficiency factor [1]
F_R (10,11)	collector heat removal factor [1]
f	subscript refering to the fluid (air)
G (14)	flow rate per unit cross-sectional area of storage bed $Kg/s - m^2$
G_c (11)	flow rate per unit of collector area $Kg/s - m^2$
H (16,23)	monthly average daily total radiation on a horizontal surface $KJ/m^2 - day$

h_1 (7)	convective heat transfer coefficient for collector absorber plate $\quad$ W/m^2 - °C
h_2 (7)	convective heat transfer coefficient for collector back plate $\quad$ W/m^2 - °C
h_r (6)	radiation heat transfer coefficient between the two air duct surfaces of collector (sides neglected) $\quad$ W/m^2 - °C
h_v (12,14,15)	volumetric heat transfer coefficient for storage bed material $\quad$ W/m^3 - °C
K_d (16,23)	ratio of the monthly average daily diffuse radiation to the daily extra-terrestrial radiation
K_t (16,23)	ratio of the monthly average daily total radiation to the daily extraterrestrial radiation
k_{air} (7)	thermal conductivity of air, taken to be constant at 0.029 W/m - °C
k_{ins} (5)	thermal conductivity of insolation used under collector, taken to be constant at 0.043 W/m - °C
L (12,15)	length of storage bed $\quad$ m
m (12,13)	subscript referring to the mth segment of the storage bed
m (9,12,13,15)	mass flow rate of air $\quad$ Kg/s
N (1,25):(20)	number of glass covers: day of year measured from January 1
Nu (7,8)	Nusselt Number
n (12,13,15)	number of segments into which the storage bed is considered to be divided for application of numerical technique
n_g (27)	refractive index of glass

Q_u (10) hourly rate of useful thermal energy collection per unit area of collector surface W/m^2

R_b (16,17,23) ratio of radiation on a tilted surface to that on a horizontal surface

$R_{e_{D,H}}$ (8,9) Reynold's Number for collector air flow based on hydraulic diameter

r_d (16,21,23) ratio of hourly to daily diffuse radiation

r_t ratio of hourly to daily total radiation

S (19,23) hourly flux of solar radiation absorbed by collection surface W/m^2

SI (16) hourly flux of solar radiation striking a tilted surface W/m^2

S (23) shading factor

T_{amb} (1,10) ambient temperance °C

$T_{c,i}$ (10) inlet air temperature to the collector °C

T_{b_m} (12,13) temperature of pebbles contained in storage segment m

T_{f_m} (12,13) temperature of air entering storage segment m °C

$T_{f_{m+11}}$ (12,13) temperature of air leaving storage segment m+1 °C

$T_{f,m}$ mean fluid temperature in collector

T_p (1) mean absorber plate temperature during operation of collector °K

T_s (13) temperature of the surroundings containing the storage bed °C

$\bar{T}$ (6) mean temperature for radiation between the absorber plate and back plate of collector, assumed constant at 340°K

T_1 (6)   mean temperature of absorber plate   °K

T_2 (6)   mean temperature of back plate   °K

t_{ins} (5)   thickness of insulation behind back plate   m

U_b (5)   overall collector back loss coefficient
W/m^2 - °C

U_L (10,11)   overall collector loss coefficient
W/m^2 - °C

U_{Ls} (13)   overall storage loss coefficient W/m^2 - °C

U_t(45°) (1,4)   overall collector top loss coefficient
for a unit tilted 45 from the horizontal
W/m^2 - °C

$U_t(\beta)$ (4)   overall collector top loss coefficient
for a unit tilted degrees from the
horizontal W/m^2 - °C

V (3)   wind velocity, assumed constant at 5 m/s

α solar altitude

$\alpha(\theta_t)$ (24,28)   directional absorptivity of collector plate

β (4,16,23)   collector tilt from horizontal

γ (18)   surface azimuthal angle (due soth being
zero and east positive)

δ (18-20,22)   declination

ϵ (13,15)   void ratio of storage bed

ϵ_g (1)   emissivity of glass cover plates

ϵ_p (1)   emissivity of absorber plate

ϵ_1 (6)   emissivity of absorber plate

ϵ_2 (6)   emissivity of back plate

θ_t (17,18,24-27)   angle of incidence of direct radiation
measured from the normal to the collector

θ_2 (26,27) angle of refraction

μ (9) absolute viscosity Kg/m-s

ρ (13,15) density of pebble bed material Kg/m^3

ρ_{gr} (16,23) diffuse ground reflectivity

$\rho(\theta_t)$ (25,26) reflectivity of a single air-glass interface for direct radiation as a function of ϕ_t

$\rho(60)$ (24) reflectivity of a single air-glass interface for diffuse radiation

τ (12,13,15) time s

$\left.\begin{array}{c}(\tau\alpha)_{eff,b}\\(\tau\alpha)_{eff,d}\end{array}\right\}$ (23) effective transmittance - absorptivity product for direct (beam) radiation and diffuse radiation, respectively

$\tau(\theta_t)$ (24) directional transmittance of glass as a function of θ_t

ϕ (18,19,22) latitude (north positive)

ω (18,19,21) hour angle (solar noon zero and morning positive)

ω_s (21,22) hour angle corresponding to sunrise (and sunset since the day is assumed symmetric about solar noon)

$$\sigma = 5.6693(10)^{-8} \text{ W/m}^2 - {}^\circ\text{K}^4$$

I. <u>INTRODUCTION</u>

This study was undertaken for the purpose of developing a computer simulation of an air-type residential solar space-heating model from which to determine the optimum collector and storage size for a given heat load. Furthermore, the need for comparison between this and liquid-type systems dictated that the model developed be adaptable to changes in various significant parameters and components.

To date the majority of published computer simulation models, as well as actual installations, has been of the "liquid-type", that is, a solar heating system wherein water or a water-antifreeze solution is the working fluid [7]. The most noteable exception to this trend has been the simulations and installations of Dr. G. Löf.

Liquid-type systems are favored [7] for commercial installations where a large amount of energy must be distributed. In such a case the storage tank, piping and insulation required occupies far less valuable space than would the storage and ductwork necessary to transport the same amount of heat using air at reasonable rates of flow. Also, the basic components (heat exchangers, pumps and controls) associated with the liquid-type system become proportionally less expensive as the size of the system they serve grows.

On the scale of a single-family dwelling however, it appears a trade-off becomes practicable between liquid and air systems depending upon the geographic location, nature of an existing conventional system (for retrofit solar installations) and extent of solar energy utilization desired, among other considerations. Some salient trade-off considerations of the two types of systems currently most widely employed are summarized in Table 1. Though not exhaustive, this indicates generally some of the more significant differences between the systems.

These points serve only as a first-cut at making an overall system evaluation because various design strategies may be employed to lessen the disadvantages of the liquid system or extend the utilization of the air system.

For example, if in a water-type system the space heat is supplied by blowing air over a heat exchanger directly into the room, instead of relying on natural convection from baseboards or radiators, lower water temperatures may be acceptable. Solar system efficiency increases significantly when the thermal energy is absorbed at the lowest useful temperature. This heat transfer can be accomplished at the storage container (e.g., in a rock bed or finned annulus surrounding the tank) with standard ducting distributing the heated air throughout the

TABLE 1: Comparison of relative merits of liquid and air-type solar heating systems. "Liquid" refers water or water-antifreeze solution as the thermal energy transport medium coupled to a water storage tank. "Air" refers to air as the transport medium with a rock bed for storage.

The base for comparison is space heating with additional abilities treated as advantages over this.

LIQUID

ADVANTAGES

1. smaller storage volume per unit of heat stored

2. transport network occupies smaller space

3. directly adaptable for use with absorption A/C equipment

4. directly adaptable to domestic hot water supply

5. adaptable to either forced-hot-water or forced-hot-air

6. if chilled-water air-conditioning is supplied, one distribution system serves for both heating and cooling

DISADVANTAGES

1. more complex controls, heat exchangers required in most applications, maintainance more costly

2. less efficient energy collection at temperatures required for forced-hot-water baseboard heating (140-190°F)

3. may require some treatment of transport liquid, such as: antifreeze, antiscale, anticorrosive or biocide

4. possibility of expensive damage in dwelling due to collector leakage, or to collector due to freeze-up

5. water may be scarce commodity; antifreeze (oil by-product) has uncertain future cost and availability

6. where central air conditioning is supplied, forced-hot-water heat requires parallel distribution system (pipes) for space heating

AIR

ADVANTAGES

1. simple operation, longer lifetime, less maintainance, less capital and installation cost

2. since the transport fluid is identical to the ultimate delivery medium, no heat exchanger, per se, is necessary

3. system can be adapted, though not readily, to cooling of dwelling*

4. where central air conditioning is supplied, one distribution system serves for both heating and cooling (ductwork sized for the mass flow rates associated with A/C lends itself to collection of heat at the lowest temperature)

5. air is free, rocks are plentiful and leaks are neither dangerous nor damaging

DISADVANTAGES

1. not readily adaptable (possibly not feasible) to providing source of heat for conventional air conditioning equipment

2. where (finned tube) heat exchangers are used, they must be larger than that required in a liquid-system to transfer the same quantity of energy

3. ducting and storage require more space for the same energy transport or storage, respectively

*e.g., cool storage at night for use during the day.

dwelling. Alternatively the heated water can be piped to those locations where space heat is required and air blown over a coil-type heat exchanger into the space. The latter scheme might be advantageous where space is at a premium or where the distribution network is extensive.

On the other hand, by placing a water coil within the rock bed of the air-type system or girdling the bed with such a coil, preheated or fully heated domestic hot water can be provided. Alternatively, by cooling the rock bed by night with ambient air, the dwelling can be cooled during the day using the storage as a heat sink. The materials of the rock bed being rather low in cost, it might be worthwhile to provide a separate, uninsulated storage bed a meter or so underground to be cooled at night in the above manner while also losing heat to the ground; this unit would be exclusively for summer air conditioning and sized accordingly. The main storage unit, well insulated and connected to the collector, would be used to heat domestic hot water (as described above) and would be available, as well, to provide space heating as needed on cool summer nights or days. This latter bed would be sized for winter space heating.

As can be seen, hybridization and innovation can be used to great advantage, especially in adapting to an

already existing conventional system, but makes a clear-cut
determination of the "best" system for a given situation
very difficult. Regional weather characteristics and labor
rates, the cost in dollars of one system versus another
(including various levels of component refinement in each
case) and the availability of materials (e.g. a reliable
source of water or antifreeze) only complicate further a
fundamentally complicated problem in thermodynamics. To
this end, "canned" computer simulations appear to offer the
most direct and cost-effective manner of gleaning from
the myriad of interrelationships the optimum design for a
given dwelling and location.

II. DESCRIPTION OF THE SOLAR HEATING
SYSTEM SIMULATED

A schematic diagram of the solar space heating system
employed in this study appears in Figure 1. The residence
is heated by forced-hot-air. The flat plate collector
transforms the absorbed portion of the incident solar
radiation into thermal energy which is then extracted by the
working fluid passing over the heated absorbing plate
(see Figure 2). This heat transfer is accomplished with
air, the ultimate delivery medium. When satisfying immediate
heating requirements of the dwelling, air circulates
directly between the collector and dwelling - cycle A - if
useful heat is available. When no solar energy is directly
available, the room air is circulated through the storage
medium - cycle B - if useful heat is available there. Should
there be a requirement for space heating beyond the capacity
of both these processes, auxiliary heat - cycle C - is
provided to make up the deficit. Finally, when solar
energy is available for which there is no immediate need,
the working fluid is circulated through the storage medium
transferring thermal energy thereto. As structured, the
absence of independent heat exchangers (the pebble bed is
at once the storage medium and a single heat exchanger)
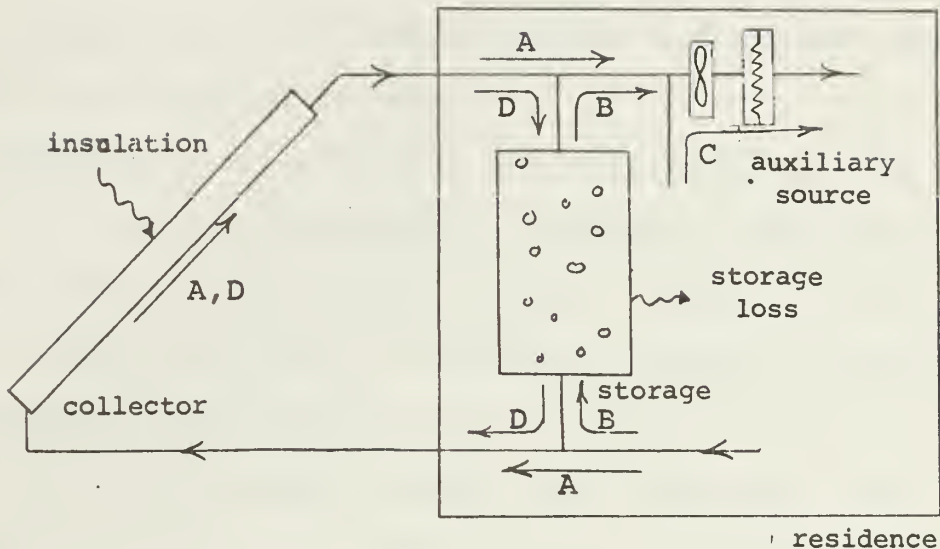
CYCLE

A   heating dwelling with collector

B   heating dwelling with storage (no
     useful heat available from collector
     directly)

C   heating dwelling with auxiliary source
     (not enough useful heat available from
     collector or storage)

D   Heating storage with the collector
     (dwelling requires no heat)

FIGURE 1:   Schematic diagram of the solar space
            heating system used in this study.
            Operational modes are listed in order
            of precedence.

disallows the ability to charge and discharge storage
simultaneously as is possible in liquid-type systems. Since
the transport fluid can also be used as the delivery medium,
however, no advantage is lost.

Auxiliary heat, necessary for those periods when no
direct or stored solar energy is available from the system,
is provided by a conventional heater. Mounted in the outlet
duct as shown in Figure 1, this heat exchanger (electrical
resistance or gas/oil fired) has an auxiliary inlet in order
that circulation through storage does not occur. An
exception to this logic could be the case where off-peak
electrical rates make charging storage with auxiliary,
off-peak energy economical thus supplementing storage input
from the collector.

The storage bed is considered to be located within
the heated space, therefore convective heat losses from
the unit are regarded as an uncontrolled gain to the room.

As shown, the location of the circulation fan would cause
a reduced-pressure in the collector. Collectors for such
systems are difficult to seal and this configuration would
allow infiltration of cold air. However, this has the
effect of lowering the overall collector temperature
resulting in more efficient operation at the expense of
lowering the collector outlet temperature. If one intends

to collect the thermal energy at the lowest useful
temperature anyway, this method would appear to offer an
advantage. This simulation does not involve such
considerations, nor does it account for pressure-drops
through storage or elsewhere. In this regard, it is
assumed peripheral calculations have addressed compatability
between mass flow rates used and various flow areas in the
system (collector and ducting cross-sections, pebble-bed
effective flow cross-section, etc.).

III.   SIMULATION OF THE SYSTEM COMPONENTS

A.   Collector

Several flat-plate collectors are available for air-type solar heating systems.   This simulation is written to accept such units when the collector characteristics have been reduced to expressions for U_L and F'.   The derivation of these terms and other factors for a given collector geometry is given in [1].   The particular collector geometry chosen for this simulation is shown schematically in Figure 2.

To reduce computing costs, the empirical relationship developed by Klein for the top loss coefficient, U_t (45°) was used:

$$U_t \ (45°) = \left[\frac{N}{(344/T_p)[(T_p - T_{amb})/(N+f)]^{0.31}} + \frac{1}{h_w} \right]^{-1}$$

$$+ \frac{\sigma(T_p + T_{amb})(T_p^2 + T_{amb}^2)}{[\epsilon_p + 0.0425N(1-\epsilon_p)]^{-1} + [(2N+f-1)/\epsilon_g] - N} \tag{1}$$

where

$$f = (1.0 - 0.04 \ h_w + 5.0(10)^{-4} \ h_w^2)(1 + 0.058 \ N) \tag{2}$$
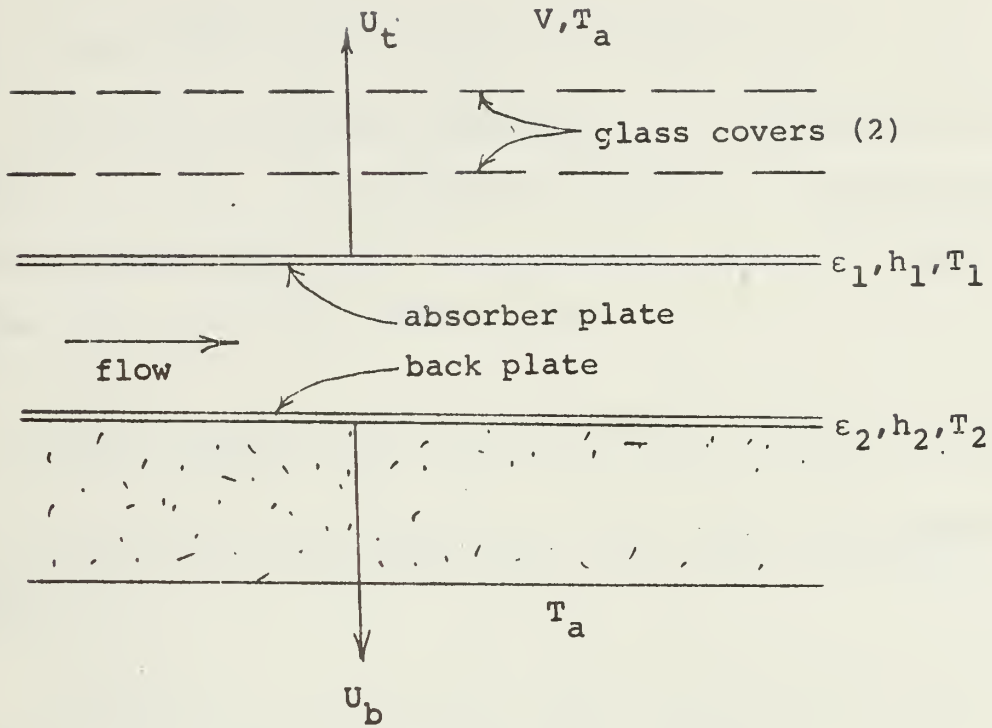
$$U_L = U_t + U_b$$

$$F' = \cfrac{1}{1 + \cfrac{U_L}{h_1 + \cfrac{1}{1/h_2 + 1/h_r}}}$$

FIGURE 2: Schematic of Collector Used in This Simulation (Elevation)

and

$$h_w = 5.7 + 3.8 \, V \tag{3}$$

(See NOMENCLATURE section for definitions)

As this expression corresponds to a collector tilt angle, β, of 45°, an additional equation to interpolate for any tilt angle (and, incidentally, for plate emissivities other than 0.95) was employed [1]:

$$U_t(\beta) = U_t(45°) \, [1 - (\beta-45)(0.00259 - 0.00144) \, \varepsilon_p)] \tag{4}$$

where f is dimensionless, V is in m/s, all temperatures are in °K and h_w, U_t (45°) and U_t (β) are in units of W/m²-°C.

In equation (1) the mean plate temperature, T_p, is not known. As a result, an iterative solution is used in the determination of U_t (45°), (see Appendix). Wind velocity, V, is taken as a constant year round but is easily varied if desired. The expression used for the back loss coefficient is:

$$U_b = k_{ins}/t_{ins} \tag{5}$$

Thus the overall collector loss coefficient, U_L, is determined to be:

$$U_L = U_t + U_b \tag{6}$$
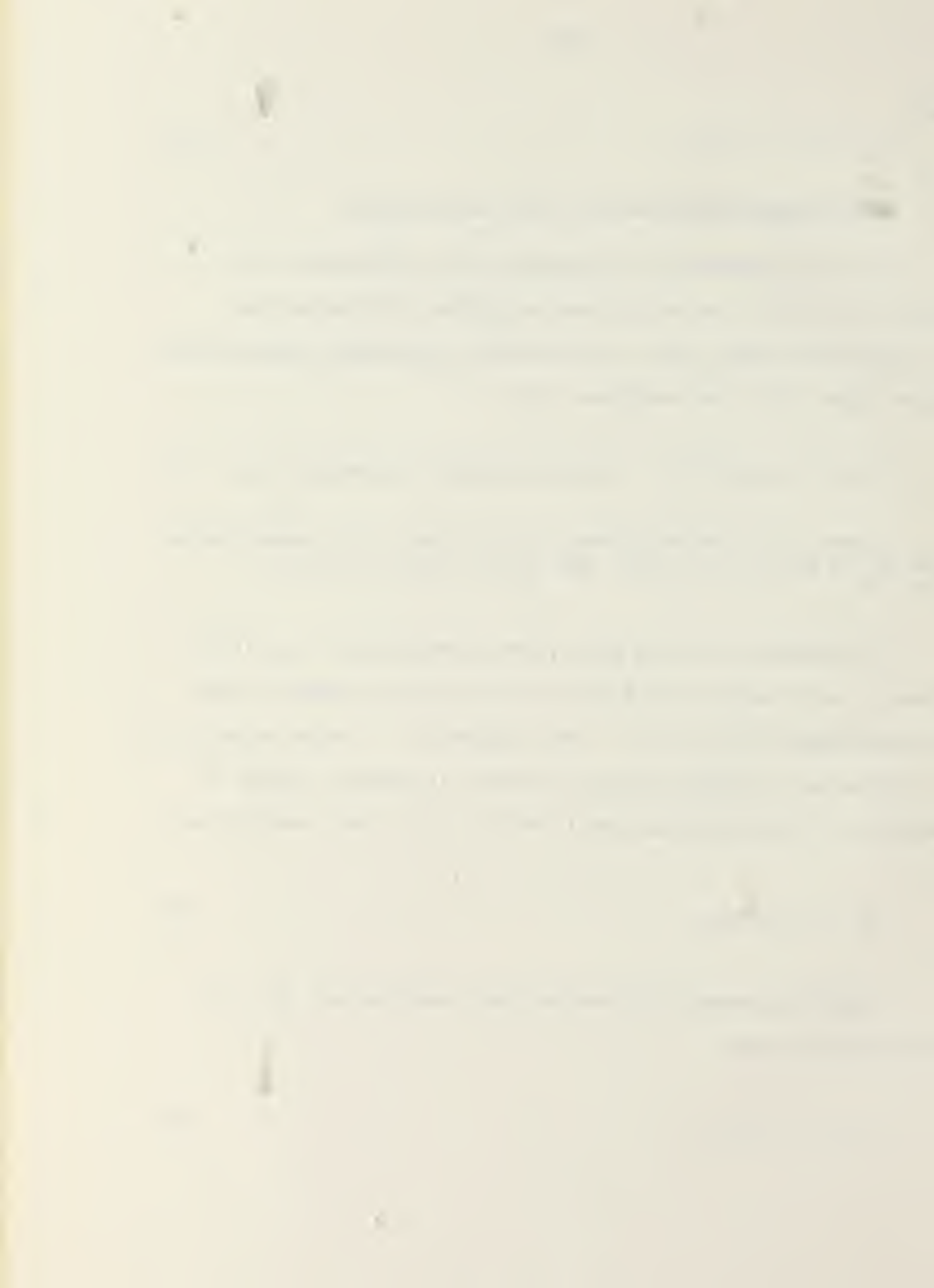
The term h_r, representing the radiative heat transfer coefficient between the back and absorbing plates (the sides of the duct being neglected in the heat transfer), is determined from the righthand-most expression below:

$$h_r = \frac{\sigma(T_1+T_2)(T_1^2+T_2^2)}{1/\epsilon_1+1/\epsilon_2-1} \approx \frac{4\sigma\bar{T}^3}{1/\epsilon_1+1/\epsilon_2-1} \tag{7}$$

where $\bar{T}$, the mean temperature for radiative heat transfer, is taken as 340°K. This assumption is not critical for the varying conditions encountered in normal operation [1].

The convective heat transfer terms - h_1 and h_2 -, taken to be equal, are based on a fully developed forced turbulent air flow between the parallel, flat plates. For the mass flow rate and all the collector sizes used in this simulation, the Reynold's Number (based on the hydraulic diameter) was greater than 2100 and the length-to-diameter ratio is larger than 10, thereby justifying the assumption. If this is not the case, one must consider the effect of the developing boundary layer (see Section 4.13 of [1]). The resultant expression is:

$$h_1 = h_2 = Nu\ (k_{air}/D_H)\ , \quad W/m^2-°C \tag{8}$$

where

$$N_u = 0.0158 \left(\frac{m \, D_H}{A_{xs} \, \mu} \right)^{0.8} \tag{9}$$

With these relations and that for U_L, F' is determined:

$$F' = \frac{1}{1 + \dfrac{U_L}{h_1 + \dfrac{1}{1/h_2 + 1/h_r}}} \tag{10}$$

Depending upon the current temperature of the room or storage "cool side" (either of which might be the collector inlet temperature depending on the operating mode in effect) the energy absorbed by the collector may or may not be available at a useful temperature. The expression for useful energy gain from the collector per unit area in either case is [1]:

$$Q_u = F_R \, [S - U_L(T_{c,i} - T_{amb})] \tag{11}$$

where F_R is the collector heat removal factor equal to [1]:

$$F_R = \frac{G \, C_p}{U_L} \, [1 - \exp(- U_L F'/G \, C_p)] \tag{12}$$

In the simulation, if the derived quantity Q_u is negative or zero, the collector is not operated. Assuming S, the absorbed solar energy (see equ. (24)) is positive the inter-pretation of a negative value of Q_u is that if run, the collector

would be operating at an average temperature too high relative to the energy being absorbed to result in an increase in fluid temperature. Expressed differently, more thermal energy would be lost to the surroundings than is being absorbed by the collector.

Due to the long-term nature of the energy balance simulated, the thermal capacitance of the collector was neglected. This is justified because the thermal energy "lost" in bringing the collector to operating temperature in the morning, is subsequently returned to the system at the end of the solar collection period. If the time response of the system were of interest, for control purposes for example, this simplification would not be valid.

Neglected also was a consideration of the trade-off involved between collecting marginal amounts of useful energy and the electrical energy expended by the circulation fan to do so.

Collector tilt was taken to be about 20° greater than the latitude which emphasizes that this simulation intends to size the collector for midwinter heating. Between the practical range of tilt angles (latitude $\pm$ 23.45°), particular angles favor particular collection schemes. For example, β = (latitude + 23.45°) results in the largest

ratio of absorbed-to-incident solar energy occuring on December 21 - this favors space heating. If β = (latitude - 23.45°), the largest ratio occurs on June 21 and favors energy collection on that day.

This simulation assumes an absorber plate emissivity for long wave radiation of 0.95. With selective surfaces available at higher cost, this value can be depressed while maintaining reasonable solar absorptance values. When mass-production techniques are employed to reduce the cost, the significant increase in absorbed energy should justify the additional expense.

The effect of dust on the coverplates is accounted for as is shading due to the collector frame work. The number of covers is taken to be two. Ground reflectance [1] is taken as 0.2 year-round which is conservative because a value of 0.7 is suggested when there is snow cover.

See Section III.E. for the equations used to determine S, the absorbed portion of the radiant energy SI incident upon the outermost coverplate of the titled collector.

B. Storage

The pebble bed storage model is taken from Mumma and
Marvin [2]. Two difference equations comprise the mathematical
model with one derived from an air-side energy balance
and the other from the pebble-side. The equations used
are [2]:

$$T_{f_{m+1}} = (T_{f_m} - T_{b_m}) \exp[-(h_v\, AL)/\dot{m}\, C_f\, n)] + T_{b_m} \quad (13)$$

and

$$T_{b_m}(\tau + \Delta\tau) = \frac{[\dot{m}\, C_f(T_{f_m}(\tau) - T_{f_{m+1}}(\tau)) - U_{Ls} A_p(T_{b_m}(\tau) - T_s)]}{(\rho AL/n)(1-\varepsilon) C_b}$$

$$+ T_{b_m}(\tau) \quad (14)$$

where subscript f refers to the air, subscript b refers to bed
material (rock), τ is time and subscript m refers to one of
the n segments into which the storage bed is divided for using
the model. Other terms are defined in NOMENCLATURE.

The term h_v is the volumetric heat transfer coefficient
defined by [1]:

$$h_v = 650 \left[\frac{G/A}{D}\right]^{0.7} \frac{W}{m^3 - {}^\circ C} \quad (15)$$

The procedure to use these equations is [2]:

(a)   Assume an initial bed temperature distribution
      at time equal zero.

(b)   For a specified bed inlet fluid temperature,
      evaluate the fluid temperature entering and
      leaving all n sections of the bed using
      equation (13).

(c)   Evaluate the new bed temperatures at each
      section after a time increment $\Delta\tau$ using
      equation (14).

(d)   Step forward in time by $\Delta\tau$.

(e)   Return to step (b) and repeat.

The "specified bed inlet fluid temperature" is either
the room temperature or collector outlet temperature
depending upon the operating mode. The time step, $\Delta\tau$ in
seconds, can be any value between 0 and 3600 in this
simulation, corresponding to the various operational
profiles which are possible. In order to insure that the
solution be stable, the time step in use must satisfy
the following, [2]:

$$\Delta\tau \leq \frac{(\rho AL/n)(1-\varepsilon)c_b}{\dot{m}\, c_f[1-\exp(-h_v AL/\dot{m}\, c_f\, n)]} \tag{16}$$

The computer simulation used automatically determines the largest number of storage sections, n, which will insure a stable solution for the largest possible time step which may occur - 3600 sec.

In a well-designed storage bed the pebble size is small enough that the temperature gradient in the individual pebbles is insignificant [1]. Physically this means the only significant resistance to heat transfer to or from the storage medium is that due to the convective heat transfer phenomenon occuring at the surface of the pebbles.

The convective heat transfer coefficient associated with the surface of the pebbles represents a thermal resistance over which we have little control. On the other hand, we can manipulate to some extent the thermal response of the interior of the pebbles by advantageously choosing the size and shape of the pebble in relation to its material composition. It is generally accepted [3] that if the Biot number (representing the ratio of internal resistance to external heat transfer resistance) is less than 0.10, then computational error resulting from assuming a uniform temperature within the pebble will be less than 5%. This assumption has been made here in order to represent the

volumetric heat transfer coefficient, h_v, by equation (15). If the pebble size is to be varied to examine the effect, this should be taken into account.

The void ratio, ϵ, is chosen to be 0.3. This corresponds to a body-centered-cubic packing arrangement of exactly similar spheres. Practically, this is the smallest ratio which might occur.

Early trial simulations included unsteady conduction in order to destratify the temperatures in the storage segments while storage was idle. The standard explicit numerical technique used [3] introduced unacceptable errors due to the relatively large longitudinal dimension of the storage segments. This length is dictated by other stability requirements. An implicit method may have improved the results but, no such capability is presently included in this simulation. Though less elegant, it is believed no misrepresentation of the storage response occurs due to neglecting this effect.

During the heating season, taken here to be September through May inclusive, the storage bed is assumed to be located within the residence such that convective losses from storage are not "lost" at all but contribute to the thermal energy requirements of the dwelling.

For the months of June, July and August it is assumed
these losses take place to the ambient temperature.
In actual practice the storage bed would probably be
located in the basement of the dwelling where some of the
convective loss would be recovered but a significant
portion would be lost to the ground. In order to avoid
unnecessary complication, the rather artificial device of
locating the storage bed based on the season was used in
order not to unreasonably misrepresent one operating
mode more than the other.

All the fluid and storage material (rock) properties
were considered constant at mean system operating
temperature values (see Table 2).

C.   Residence

The residence is modeled as a degree-day heat sink.
It was chosen to correspond in that characteristic, and size,
to that used by Butz [4] in his water-type system (17,000 Btu/
°F-day = 374 w-hr/°C-hr). Assumed to be a box-like structure,
it has dimensions of 45' x 40' x 8' with standard
construction materials, 3 inches of insulation, 2 x 4's
on 16-inch centers and 15% fenestration. The effects of
heat loss through the floor, infiltration of outside air,
solar radiation through unshaded windows and internal heat
generation from occupants and electrical appliances were
considered by Butz. Considering only the walls, roof and
windows as media through which conductive and convective
heat transfer may take place, one arrives at a figure of
18,200.0 Btu/°F-day; a 7% error which overpredicts the energy
need. It appears a much less strenuous calculation may be
adequate to characterize a residence.

The model produces data based on the following
assumptions regarding a desirable home heating scenario:

(i) During the heating season the comfort range is
between 67.0-70.0°F (19.4 - 21.1 °C) between the hours
of 0630 and 2230 and 62.0 - 65.0°F (16.7 - 18.3 °C) for

the remainder of the 24 hour period. For the purpose of
determining storage loss to the surroundings or collector
inlet temperature during direct residence heating from the
collector, the mean of the desired temperature range in
effect is used. It is tacitly assumed that the residence
is within the desired temperature range at all times by
some combination of direct, stored or auxiliary energy.

(ii) During June, July and August the desired room
temperature is between 70.0 - 73.0°F (21.1 - 22.8 °C)
between hours of 0630 and 2230 and 65.0 - 73.0°F (18.3 -
22.8°C) for the remainder of the 24 hour period. Although
during these months storage temperatures are allowed to
be 180°F (a temperature too high to be acceptable for space
heating), space heating would in fact be possible with a
simple mixing damper in the ductwork. The effect would be
to divert only part of the fixed air flow through storage.
The present model does not account for this possibility and
simply provides auxiliary heat when necessary during these
summer months.

(iii) If the ambient temperature is greater than the
desired room temperature but less than the maximum acceptable
room temperature (73.0°F) no input of any kind is provided.

D.   <u>Auxiliary Heat</u>

Auxiliary heat is supplied in the amount necessary to make up the deficit between that which the solar heating system is able to provide (including uncontrolled storage losses to the room) and that required by the residence.

E.   Insolation and Weather

The method of Liu and Jordan [5] was used in this simulation to provide insolation input. The development and application of this method follows directly that of Felske [6]. In this approach, actual hourly values of insolation for an entire year are unnecessary. Instead, this method requires only that the monthly average values of H, K_T and K_d be determined for a given location. These terms are defined in NOMENCLATURE and [5] explains how they are derived. The location used in this study was arbitrarily chosen to be New York City (40.77°N).

With the above parameters determined for each month, one is able to calculate for an average day of that month, the <u>hourly</u> flux of solar radiation incident upon the collector from the equation [6]:

$$SI = r_d H \{ \underbrace{[R_b (1-K_d/K_t)]}_{\text{beam}} + \underbrace{[1/2 \ (1+\cos\beta) K_d/K_t]}_{\text{diffuse sky}}$$

$$+ \underbrace{[1/2 \ (1-\cos\beta)\rho_{gr}]}_{\text{diffuse ground reflection}} \} \qquad (17)$$

where it is assumed that $r_t = r_d$ and:

$$R_b = \frac{\cos \theta_t}{\sin \alpha} \tag{18}$$

$$\cos\theta_t = \cos\delta \cos\omega (\cos\gamma \sin\phi \sin\beta + \cos\phi \cos\beta)$$

$$+ \sin\gamma \sin\beta \cos\delta \sin\omega$$

$$+ \sin\delta(\sin\phi \cos\beta - \cos\gamma \cos\phi \sin\beta) \tag{19}$$

$$\sin\alpha = \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega \tag{20}$$

$$\delta = 23.45 \sin [360 (284 + N)/365] \tag{21}$$

$$r_d = \frac{\pi}{24} \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \tag{22}$$

$$\cos\omega_s = - \tan\phi \tan\delta \tag{23}$$

where N is here the number of consecutive days to mid-month, measured from January 1. When the quantity SI is negative or zero the collector was not operated.

Of course the insolation striking the tilted, outermost surface of the collector is not the energy which ultimately reaches the absorbing plate. The hourly rate of radiation

striking and being absorbed by the collector plate (accounting

for dust, shading, reflections and absorption) was computed

from the relation [6]:

$$S = (\tau\alpha)_{eff,b} \; r_d H [R_b \; (1-K_d/K_t)]$$

$$+ (\tau\alpha)_{eff,d} \; \frac{r_d H}{2} [(1+\cos\beta)K_d/K_t + (1-\cos\beta)\rho_{gr}] (1-s)(1-d)$$

(24)

where from [6]:

$$(\tau\alpha)_{eff} = \frac{\tau(\theta_t) \; \alpha(\theta_t)}{1-[1-\alpha(\theta_t)]\rho(60°)}$$

(25)

and

$$\tau(\theta_t) = \frac{1-\rho(\theta_t)}{1+(2N-1)\rho(\theta_t)}$$

(26)

$$\rho(\theta_t) = \frac{1}{2} \left[\frac{\sin^2 (\theta_2-\theta_t)}{\sin^2 (\theta_2+\theta_t)} + \frac{\tan^2 (\theta_2-\theta_t)}{\tan^2 (\theta_2+\theta_t)} \right]$$

(27)

$$\theta_2 = \sin^{-1} \left[\frac{\sin\theta_t}{N_g} \right]$$

(28)

in which N equals the number of glass cover plates and other
terms are defined in NOMENCLATURE.

Reference [6] indicates that the directional absorptivity of the collector surface, $\alpha(\theta_t)$, can be represented by a curve for a typical surface. The equation provided by Felske to represent this typical curve is:

$$\alpha(\theta_t) = 1.0 - \frac{20.03}{(100.03 - \theta_t)^{1.3}} \tag{29}$$

where θ_t assumes its actual hourly value for beam radiation but is assigned the value of 60° when used to represent the diffuse radiation component [6].

The hourly ambient temperature distribution is more random than insolation and it can probably be argued that one reasonable distribution of the average daily temperature is about as good as another. In this simulation, the scheme illustrated in Figure 3 was used. The average daytime temperature and nighttime temperature were cast on a sine wave peaking at 1300 hours (Note: throughout this simulation, hourly values are referenced to solar time).
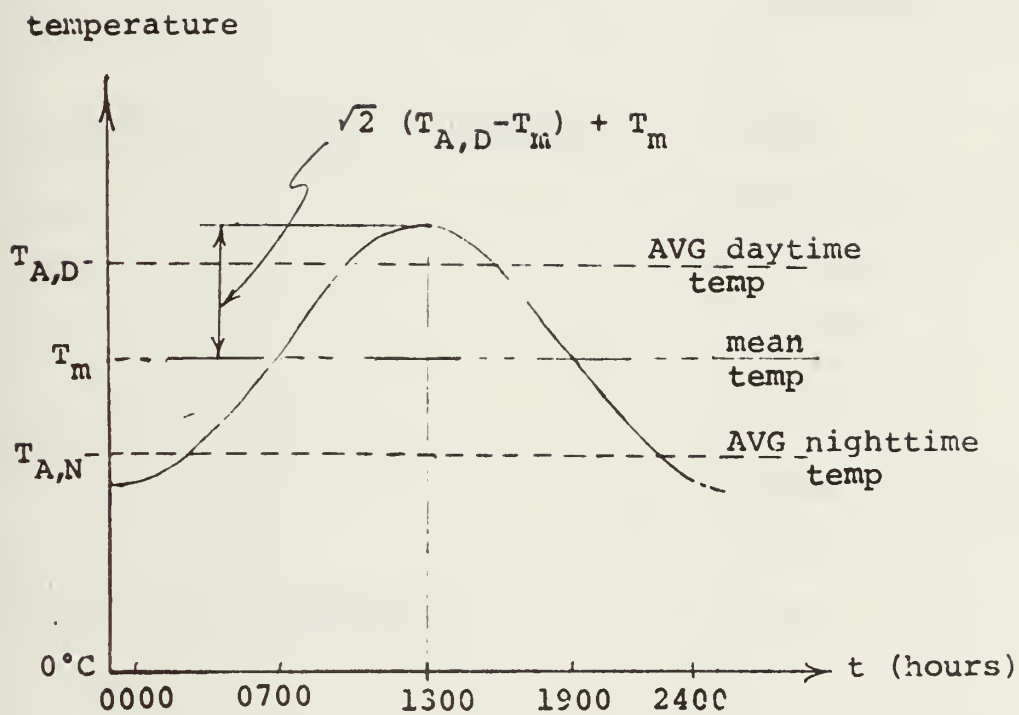
FIGURE 3: Distribution of Ambient
Temperature Through the
Day

TABLE 2

Simulation Design Parameters

c_b	0.837 KJ/Kg-°C
c_f	1.012 KJ/Kg-°C
d	0.02
Insulation thickness, collector	0.076m
k_{air}	0.029 W/m-°C
k_{ins}	0.043 W/m-°C
$\dot{m}$	1.2 Kg/s
D	0.0508m
N	2 (number of covers)
n_g	1.526
Plate spacing, collector	0.01m
s	0.03
V	5.0 m/s
$\alpha(60°)$	0.8346
β	60°
ϵ	0.3
ϵ_g	0.88
ϵ_l	0.95
γ	0.0

μ (absolute viscosity)	$1.912(10)^{-5}$ Kg-m/s
ϕ	$40.77°$ N
ρ	2400 Kg/m^3
ρ_{gr}	0.2

TABLE 3

Approximate Time Constants for Major System Components

Values for collector and storage are based on the basic
component parameters, assumed constant at approximately the
mean operating temperature associated with each component.

The value for the residence is calculated based on
the time to change the interior temperature of the author's
home a given number of degrees over a period of time with
constant ambient temperature and no heat input.

Collector:	1/4 hour
Storage Bed:	1 hour
Residence:	10 hours

IV.   OPERATIONAL LOGIC AND STRATEGY

The flow chart of Figure 4 represents the operation of the solar system. A breakdown of the computer logic used to implement this basic logic appears in the Appendix.

This simulation operates by accounting for the following heat transfers from and into the residence unit:

a.   The heat loss from dwelling driven by the difference between the desired room temp- erature and ambient temperature.

b.   Heat supplied directly to the dwelling from the collector on an as-needed basis when available.

c.   Heat supplied to the dwelling from the storage bed in the form of either uncontrolled con- vective losses or forced-hot-air plus the uncontrolled losses.

d.   Heat supplied from the collector to the storage bed.

e.   Auxiliary heat as necessary to meet what remains of the heat load should sources (b) and (c) prove insufficient to meet the entire demand.

-45-
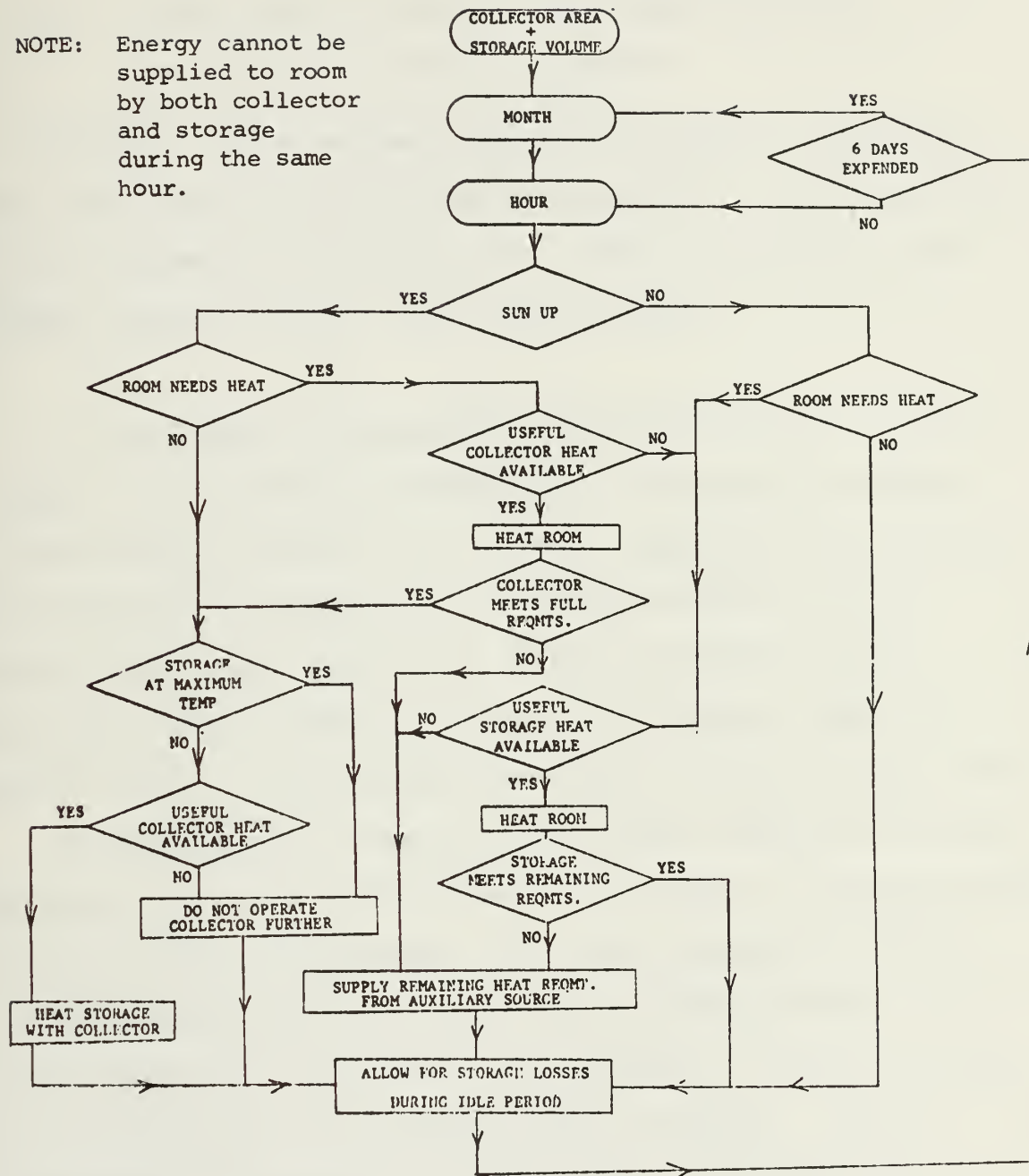
FIGURE 4 Flow Diagram of Overall Simulation Logic
(Refer also to Figure A.2)

    f.   Total useful thermal energy obtaining from

          the collector for all purposes.

The only temperatures monitored or used as controlling input are those of the storage bed segments. The temperature of the residence is assumed at all times to be within the comfort range in effect for a given season.

To implement the insolation representation of Liu and Jordan [5], it has been assumed that the monthly average of the hourly insolation and ambient temperature applied for one 24-hour period predicts the system behavior for the entire month when the results of this "average" day are multiplied by the number of days in the month. Butz [4] used a similar extrapolation with hourly Weather Bureau data.

A discontinuity occurs in the system operation in going from one month into another due to the change in these monthly average values. Furthermore, the final temperature profile in the storage bed carries into the succeeding month. For these reasons the first days of operation in any given month do not represent a true average daily response. If the simulation is operated for several days utilizing the insolation and ambient temperature profiles of that month, the influence of the starting conditions is eliminated. A

measure of the degree to which the starting conditions have been obscured is the correspondence between storage bed temperature profiles separated by 24 hours of operation.

For the ranges of parameters and values of constants used here, 4 to 5 days operation served to damp out starting effects in most cases. Therefore, the following strategy was used:

   i.   For each month, 9 full days of hourly operation were simulated.

   ii. The last run (corresponding to the 9th day) is used as the "average" day. The results obtained for this day are multiplied by the number of days remaining in the month.

  iii. The results for the entire month are obtained by adding the cumulative results of the first 9 days to those obtained in (ii).

During the heating season, the maximum allowable average temperature of the storage bed is chosen to be 145°F. In the limit, then, this is the highest possible forced-air temperature which can be derived from storage. This temperature is at least 20°F below that which outlets from a conventional forced-hot-air heating unit where common practice indicates a rise in temperature of 100°F or more

through the furnace [8]. This lower operating temperature
allows more efficient operation of the collector but requires
a higher-than-conventional mass flow rate of warm air into
the room. The codes [8] restrict the rate of room air change-
out and must be consulted. If upon supplying the hourly
room needs the collector is able to bring storage to this
temperature, the collector ceases to operate. Subsequent
collector-to-storage operation is only to the extent necessary
to maintain this temperature in the face of demands made upon
storage. This mode of operation causes the low usefulness
ratios (useful heat collected/incident thermal energy) in
early fall and late spring.

During the summer months when this simulation does not
supply solar space heating, the maximum storage temperature
is allowed to be 180°F for the purpose of domestic water
heating. Higher temperatures are possible if pressure relief
and mixing values are used in the water system but then the
collector would operate less efficiently. 180°F was chosen
to avoid unnecessary complication. No attempt is made to
model a realistic daily hot water usage scenario in the summer.
Instead, the heating load presented to the bed is that of an
increased convective heat loss coefficient corresponding
approximately to an 80 gal/day draw-down of 100°F water spread
evenly through the 24-hour day, added to the previously used

coefficient. Accurate assessment of the water heating mode does not contribute to the objective of this study; this portion of the simulation is included only for continuity.

If the collector can heat the dwelling directly but is unable to meet the full requirement, auxiliary heat is used to make up the deficit. In this situation the only contribution from storage is the uncontrolled convective loss. This strategy is used in order to obtain all the useful solar energy available and does not consider the electrical energy required by the circulation fan to obtain this marginal amount of thermal energy.

Several arbitrary choices have been made as to what constitutes a desirable system operation.

    i.   If when heating storage with the collector the increase in average bed temperature corresponds to a thermal energy input of less than 3.3 W-hr in one minute (an hourly rate of 200 W), the system is not operated.

    ii. When heating the room from storage a 1% overshoot of the room's needs is tolerated. The overshoot shows up as excess heat which is subtracted from the otherwise useful energy gain of the system and results from the time step used (see iv).

iii. If at any time while heating the room from
storage the thermal energy added in one minute
is less than 5% of 1/60th the total hourly room
need, then the system is relaxed and the
auxiliary source provides the remainder of
the heat load.

iv. All heat transfers to and from storage are
accomplished in 1-minute intervals. If some
fraction of a minute over the hour is used or
an unacceptably large overshoot in energy input
occurs, the 1-minute interval in which this
occurred is nullified and the process continues
in 5-second intervals. Any further overshoot
resulting during such a reduced interval is
accepted and appears as an accountable excess.

When heating storage from the collector, the inlet
temperature to the collector is held fixed for the duration
of the hour at its value at the beginning of the hour.
In fact this temperature increases as the bed is heated
and, if strictly accounted for, could result in a decrease
in useable thermal energy available to storage. Errors due
to this assumption are considered small considering the
small change in temperature of the storage bed which occurs

in one hour.   So, in the interest of decreasing computation
time, the effect was neglected.

V.   <u>RESULTS</u>

Figure 5 demonstrates the ability of various collector sizes to meet the heating demands of the residence used in this simulation. As collector size increases a greater proportion of the room needs can be accommodated. If analysis of cost tradeoffs and regional weather character- istics indicate that it is advantageous to use solar power for approximately half the residential heating needs in mid-winter, then this figure indicates that the 60 m^2 collector should be employed.

The curves of the ratio of solar energy obtained to room needs for various collector sizes were derived using a fixed storage volume. Figure 6 indicates, however, that mid-winter system capability for various collectors is relatively insensitive to the size of storage. The reason for this result is that for the collector sizes examined, no collector provides on a daily basis more energy than the residence consumes in that time. There is then no net accumulation of energy in storage and the total of the daily solar energy obtained reflects the room needs only.

The uppermost, flat curve of Figure 5 represents the practical limit of system output. Achieving this output requires a collector of such size that storage is
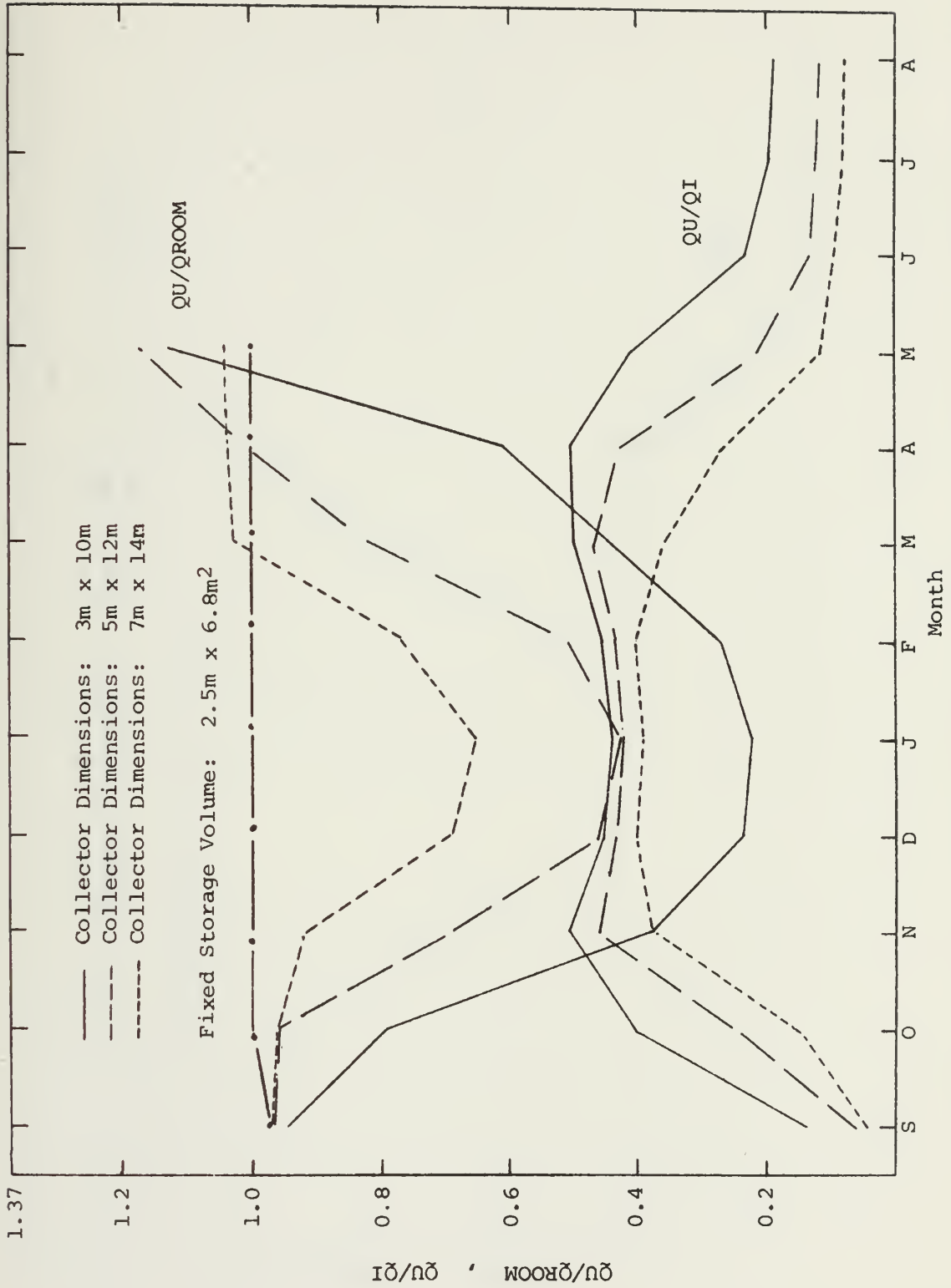
FIGURE 5   Daily Integrated Energy Ratios, Averaged by Months for Fixed Storage Volume.
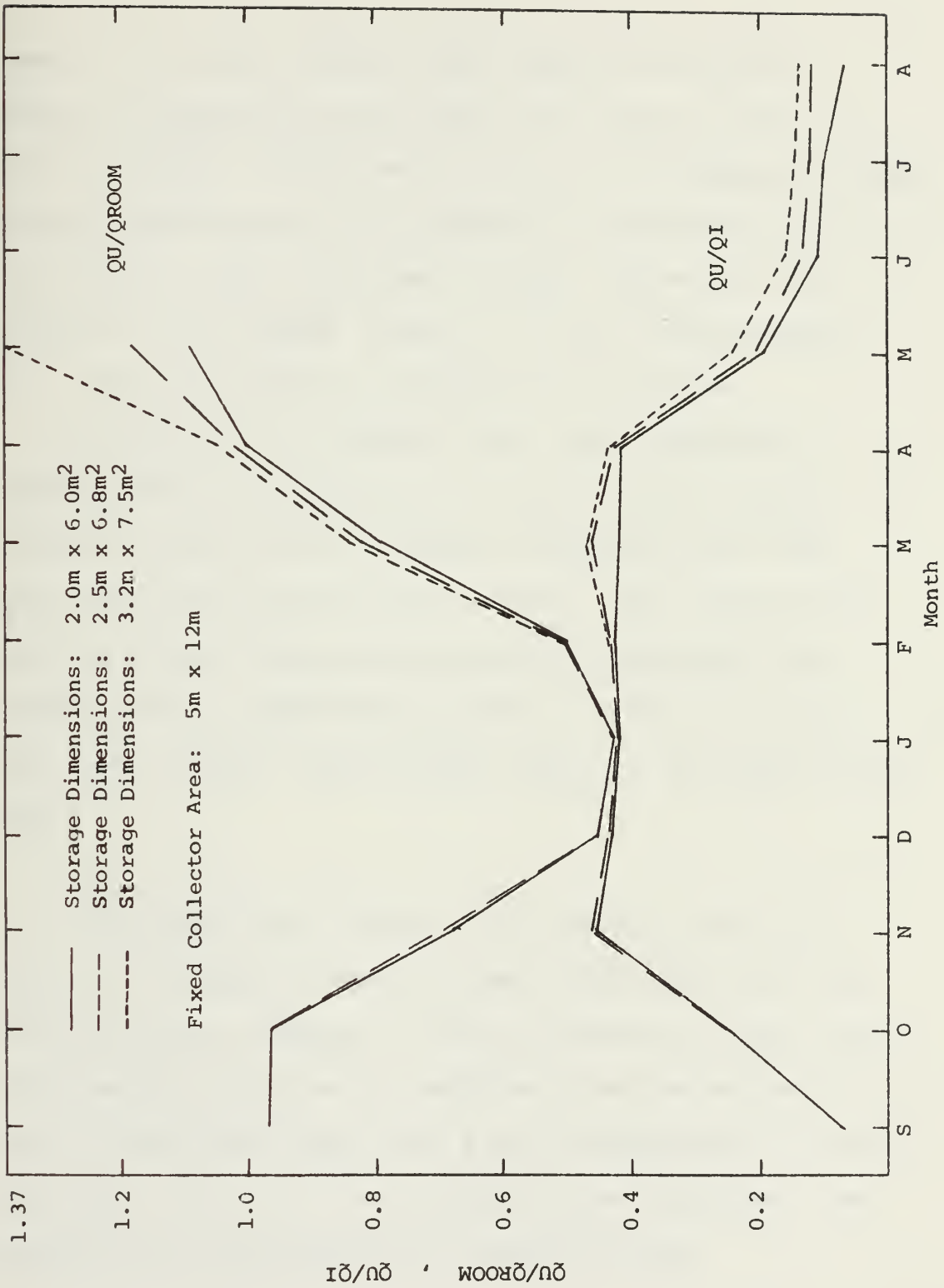
FIGURE 6   Daily Integrated Energy Ratios, Averaged by Months for Fixed Collector Area

brought to a fully charged state each day while the
immediate daytime dwelling heat load is met as well. A
"fully charged" storage bed is one at the maximum allowable
average temperature. It is assumed in presenting this
limiting case that sufficient storage volume has been
assigned to the system to meet, in full, the overnight
heat load if the bed is initially fully charged.

In Figure 5 the QU/QROOM curve (see SIMULATION
NOMENCLATURE for definition of terms) for the largest
collector used is seen to behave differently than the
other two curves during April and May. The "cross over"
observed results when the storage bed approaches the
maximum average temperature allowed. When this occurs,
very little further solar energy input to the system takes
place.

A QU/QROOM ratio exceeding the maximum practical
value of 1 is seen to occur in late spring for all three
collector sizes examined. This is because in those months
enough solar energy can be obtained from the collector to
meet the room needs and allow a net accumulation of energy
in storage. Note that as collector size increases, the
QU/QROOM curve approaches the limiting curve.

The curves of QU/QI of Figures 5 and 6 represent the ratio of solar energy collected to that incident upon the tilted collector surface. This ratio is a measure of collection efficiency. For fixed system mass flow rate of air and storage size, increasing collector area decreases collection efficiency because of the higher mean temperature of collection and storage (even if panels are added in parallel).

Efficiency is generally lower in early fall and late spring because the higher insolation and storage temperature approaching saturation cause a higher mean temperature of collection. This, in turn, drives a higher loss rate to the surroundings despite relatively warm ambient temperatures. In late fall and early spring the relation between ambient temperature, available insolation and the lower average temperature in storage combine advantageously to produce the highest efficiency. In mid-winter the low ambient temperature drives large collector losses despite the rather low mean temperature of collection (resulting from the lowest insolation and storage temperature levels of the year).

In Figure 6, the higher efficiency of larger storage beds in spring reflects the increasing level of collector-to-storage heating activity and lower collection temperatures which result from distributing about the same amount of collected energy throughout a larger mass of rock. The approach saturation which will occur as storage size decreases, rapidly increases the efficiency disparity.

Figures 7 and 8 illustrate the monthly totals of hourly solar energy supplied by the system in excess of that required. During early spring and late fall the excess is primarily caused by the uncontrolled convective storage loss. During the winter when all the storage loss is of use to the dwelling, any excess occuring is caused by an "overshoot" of storage energy input to the room during active heating with storage. This overshoot results from the time increment used in the simulation (see pg. 50 Sec. IV) and is not a characteristic of solar systems.

The excess in spring and fall is a real effect if storage is contained within the dwelling. These losses are annoying and are counterproductive to any air-conditioning employed during the day.

All three curves of Figures 7 and 8 extend to about $1.4(10)^5$ W-HR in September, off the scale presented. This occurs because storage was taken to be fully charged at the commencement of this month. The high convective heat losses which are a consequence cause the high excess energy value.

Such excesses do not occur in May because storage temperature levels do not naturally reach saturation with the available solar energy and room requirements
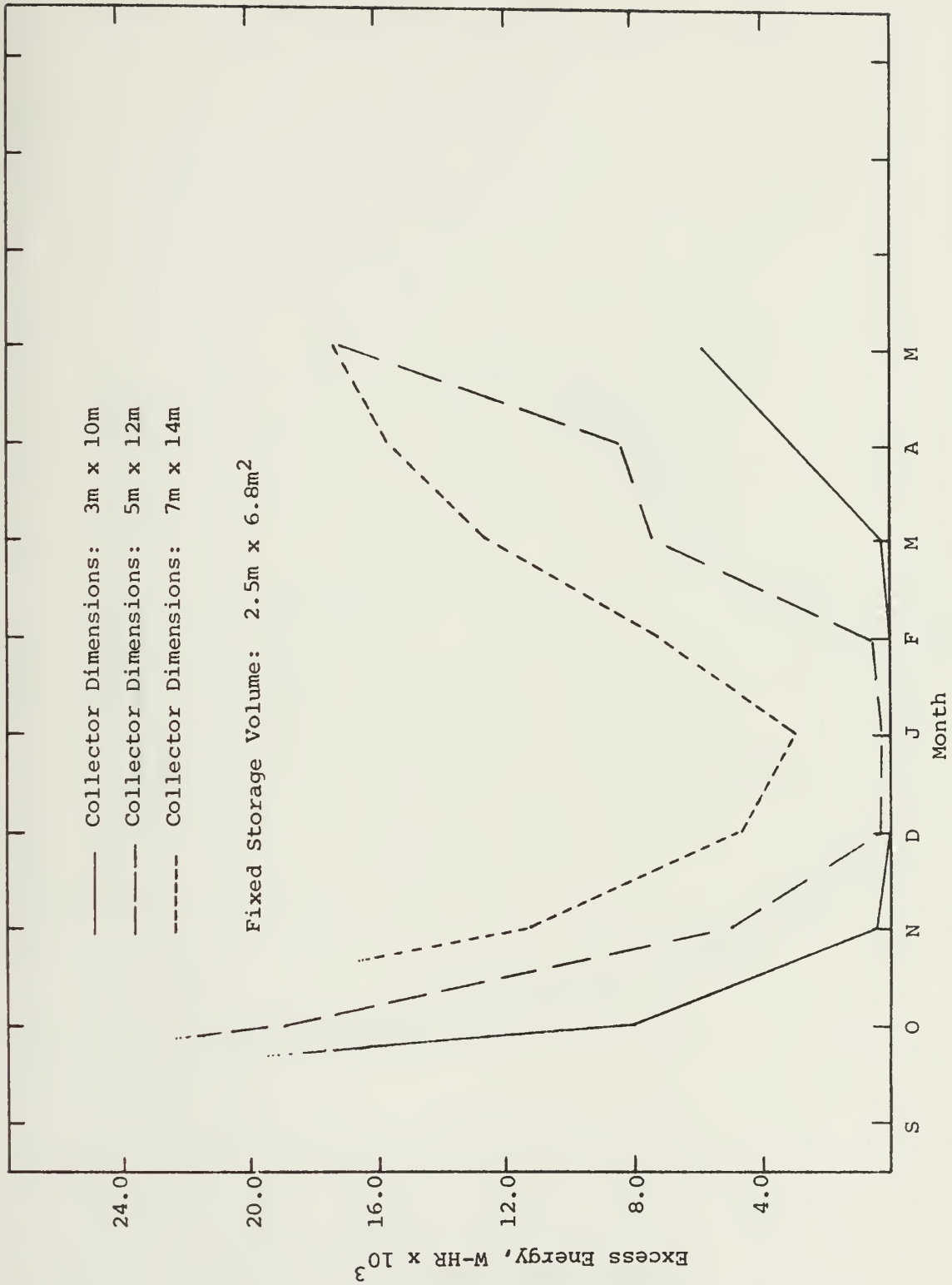
FIGURE 7 Monthly Quantity of Excess Energy, Average by Months, for Fixed Storage Volume
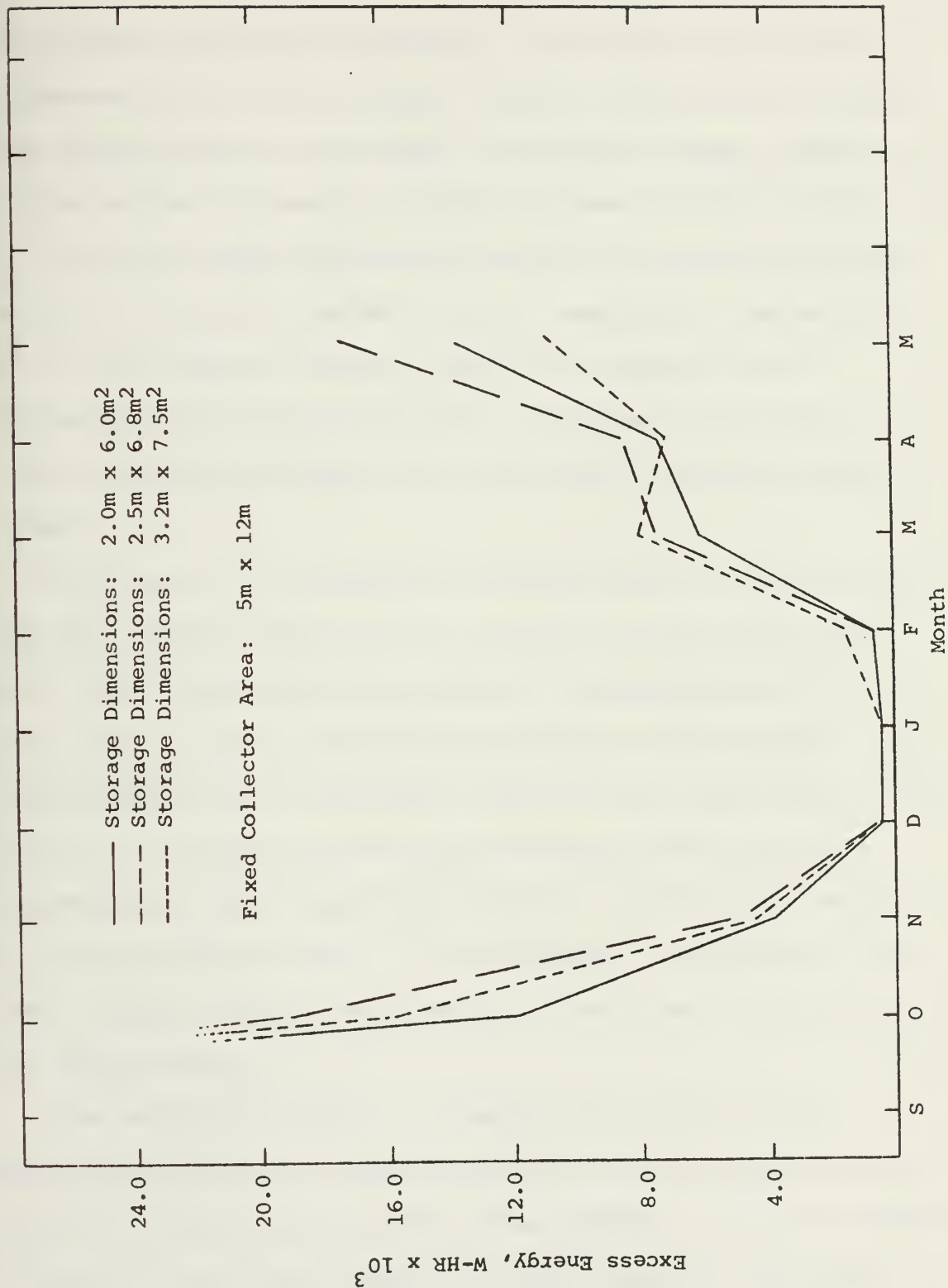
FIGURE 8 Monthly Quantity of Excess Energy, Average by Months, for Fixed Collector Area

are higher in May than September. Starting the month of
September with a fully charged storage bed simulates having
used storage during the summer for domestic water heating
at the maximum allowable average bed temperature of 180°F

The two larger collectors are seen to provide similar
amounts of energy in excess of that needed for the month of
May. This results because, again, the storage bed is
approaching the saturation level. Once near or at this
level, a larger collector will not result in more storage
losses.

In Figure 8, an apparent anomoly occurs in late spring
when the excess energy for the largest storage unit falls
below that of the other two units. An examination of the
hour-by-hour energy transfers to the room from storage
indicates that the "overshoot" flaw is the cause (see pg. 50,
Sec. iv). A lesser percentage of excess energy input to
the dwelling occurs each hour with the largest bed compared
to the two smaller units. This behavior is evidence of the
lower overall storage temperature as bed size increases, all
else being equal.

The arbitrary choice of storage size used in this
simulation happens to span the range over which an inversion
occurs in excess energy output from storage. It is observed
in Figure 8 that from October through December the excess

energy first increases with increasing storage volume then
decreases. Again, inspection of hour-by-hour energy
transfers indicates the cause. The smallest bed can provide,
in the first several hours after sundown, more hourly energy
output than larger units which have a lower average temper-
ature. This is so despite the fact that all beds contain
about the same total stored energy.

The higher hourly output from the smallest storage bed
results in more hourly overshoot. But since this bed is
depleted sooner, it is less often able to provide heat. The
cumulative overshoot is consequently less than for larger
units.

The largest unit operates to heat the room the most
number of times, but each time the overshoot is small because
of the relatively lower temperature of the energy provided.
Cumulatively, less total overshoot occurs than with the
mid-size bed but more than that occurring with the smallest.

Figure 9 shows the degree in which room energy needs are
met with the desired collector and various storage volumes.
This figure applies to the New York area for September and
October starting with a storage bed at room temperature.
For the collector size and residence of this example, the
only months during which more solar energy is provided than
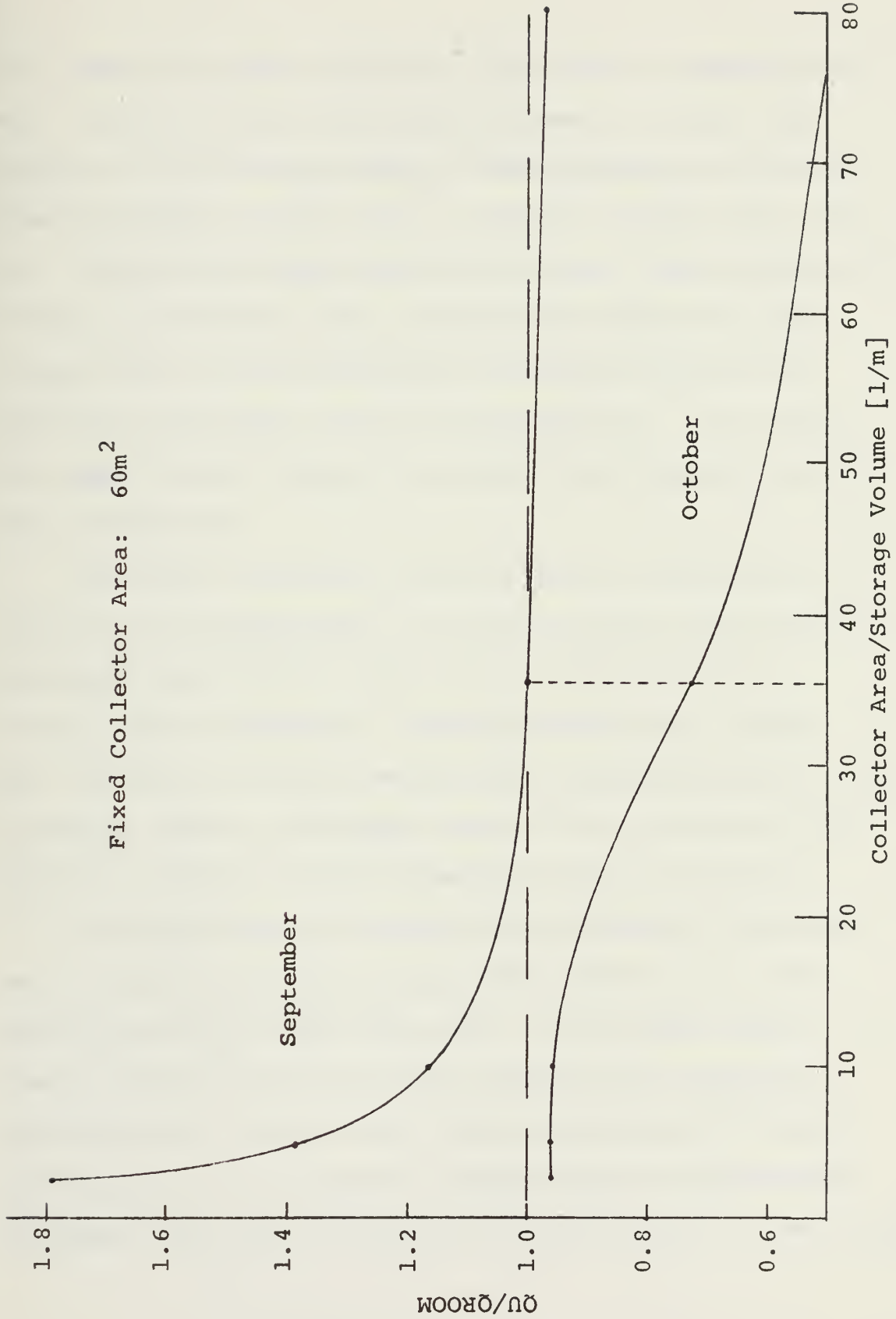
FIGURE 9   Ability of Various Storage-Collector Combinations to Meet Room Heating Needs

that required to meet the daily room needs is September and May. Either of these months may be used to "sense" the presence of the storage bed, no longer masked by the over-powering effect of room needs. Relative stroage size plays very little role during mid-winter because then storage only serves to distribute solar energy stored during the day through part of the immediately following night with no carry-over of energy into the following day. It is clear that some storage volume is necessary but that size has yet to be determined.

The dashed, vertical line of Figure 9 indicates the collector-to-storage ratio for which no more solar energy is collected daily by the system than is required for an average day in September. Allowing nothing for "cloudy days" carry-over storage capability, this system should have a storage volume in September equal to the collector area times the factor 1/35 (the dimensions being in meters).

A storage sizing criterion which optimizes mid-winter use of the solar heating system would seem to be a more rational criterion than the above. It has been shown, however, that mid-winter system operation is relatively insensitive to storage size. Within the range of storage sizes examined, the ratio of storage output to room needs increases less than 1% (see Table 4) when storage volume increases

twofold. So, such a criterion is elusive at best. Intuitively, there are limits to the range of useful storage temperatures and this suggests an upper and lower bound to storage volume exists.

If an upper temperature limit is placed on the bed (as dictated by the codes as regards delivery temperature or room air change-out rate, etc.: in this simulation 145° F was used) there is a lower storage volume which will attain, on average, this saturation temperature using all the energy available to storage on a typical mid-winter day. However, because the collector operates inefficiently due to the high temperature it receives from storage, the total energy stored is less than could have been obtained for any larger storage bed given the same conditions.

The lower limit on storage bed temperature is that which provides a comfortable influx of heating air and depends on relative humidity. Generally, normal body temperature represents a good estimate of this lower limit on storage temperature. The storage volume for which this temperature obtains when all the energy available to storage on a mid-winter day is accepted, is the upper limit on storage volume. This provides the most efficient system operation based on collected energy but the energy stored at this temperature is only marginally useful.

Lacking a definitive mid-winter storage-sizing method, it is suggested that the "September storage sizing criterion" above be adopted as a method of determining storage volume given a collector area.

In this simulation, using a 5m x 12m collector the storage volume thus indicated is $1.7m^3$. If it is assumed that the energy available to storage in January for a $6.6m^2$ x 2.5m storage volume (see Table A.1) remains constant as the storage volume decreases to $1.7m^3$, the resulting average storage bed temperature attains $115°$ F (if it starts at room temperature). Of course, due to collector inefficiency the collected energy would be less as would be the temperature attained.

Thus, an even smaller storage bed could be used without saturation occurring but less total energy would be stored.

TABLE 4

Energy input to room from storage, between sunrise
and sunset, as a percentage of room needs during
that period. Values are for January with
combinations of storage and collector sizes as
indicated.

Storage Volume (m^3)

Collector Area (m^2)	12	17	24
30		0.3%	
60	22.9%	23.6%	23.8%
98		57.9%	

VI. CONCLUSIONS

From Figures 5 and 6 it can be concluded that collector area requirements to meet a known energy need can be determined without regard to storage size.

It is unnecessary to consider increasing storage size to allow for the "carry over" of solar energy into subsequent "cloudy days" because for economically sized collector areas designed for mid-winter needs there is, on the average, no energy available for subsequent days. Only if more than 100% of the daily room requirements can be supplied from the system in mid-winter is there, on the average, a "carry over" capability which can be enhanced by increasing storage size. Collector size is the single most important consideration in installing this solar heating system.

Once the collector area necessary to meet the energy need has been determined a compatible storage volume must be derived. "Compatible storage volume" is taken to be that volume which results in a QU/QROOM ratio of 1 in September (see Figure 9). It must be realized that such compatability of collector and storage applies only to a system providing approximately 50% of the mid-winter

space heating requirement and the location for which this analysis was carried out, that is, New York.

Within the above conditions, it is suggested that the ratio 35:1 be used to relate collector area to storage volume (dimensions in meters) for a hot air system with pebble bed storage. Researchers generally quote suggested ratios of collector size per storage volume (or per person for strictly domestic water heating applications) when speaking of water-type systems. When doing so, the validity of the ratio is predicated on specifying the location and percentage to be met of the total demand. It is for this reason, with a similar claim of validity, that the ratio above is presented.

APPENDIX

The flow chart included here illustrates the simulation of the solar heating system used in this study.

The numbers appearing in the chart are keyed to the various "go to" statements used in the computer program and are included in order to guide the reader through the computer listing appended.

The terms used herein are defined in the SIMULATION NOMENCLATURE section of the appendix.

Two pages of output are presented to illustrate their form.
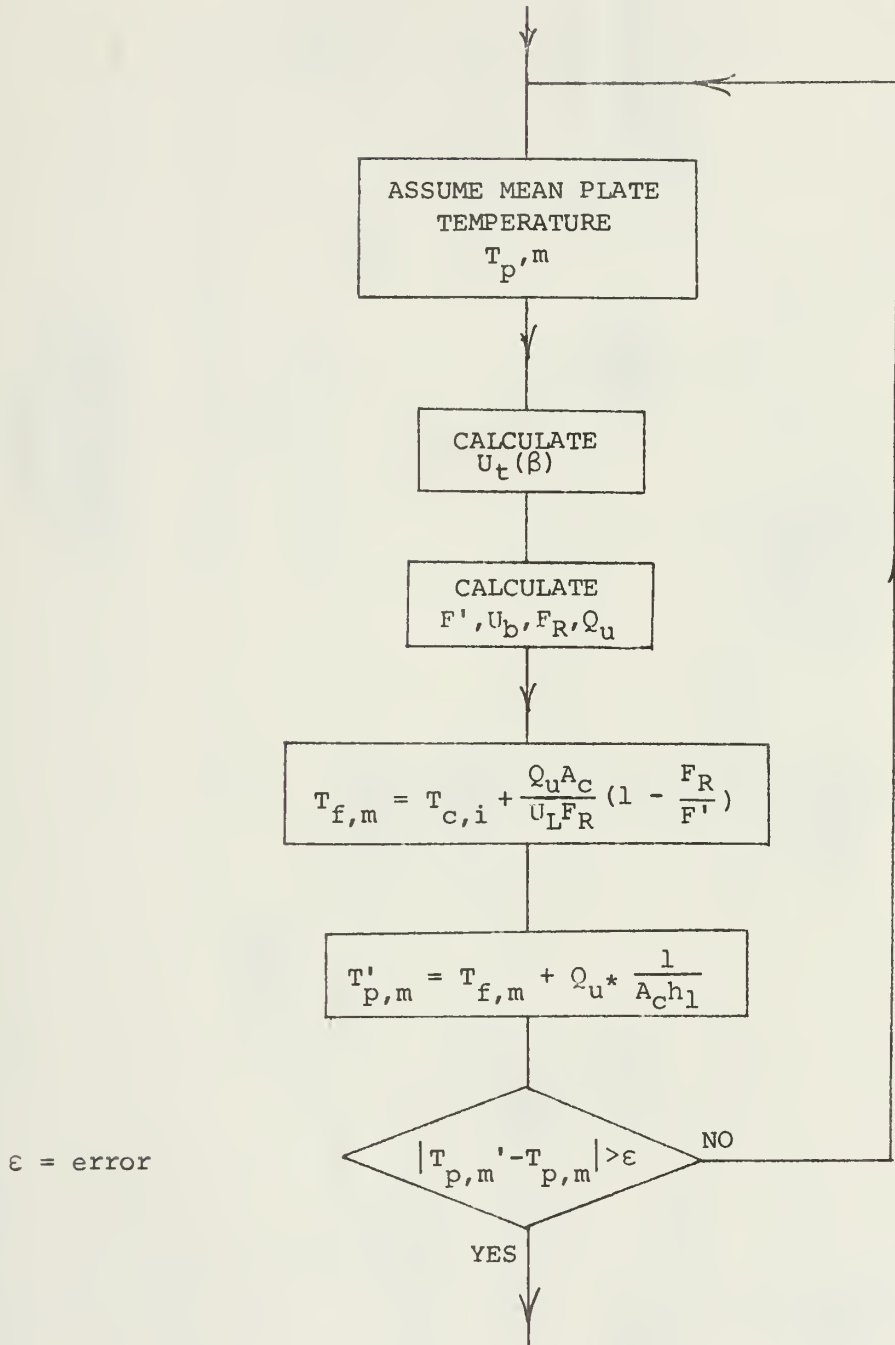
FIGURE A.1. Determining the Mean Plate Temperature [1]

FIGURE A.2. Computer Simulation of
Solar Heating System
(Refer also to Figure 4)

HEAT SURROUNDINGS FROM STORAGE

121

QADINT=ΔQPBE

QADINT>0

810

QRATIO=ΔQPB/(QROOM/60)

QRATIO>5%

QRMFNS=QADTOT

QRMFNS=QRMFNS+ QPB
QAUX=QROOM-QRMFNS-QRMFMC
QXCES=|QAUX| if QAUX<0

RTN

QRMFNS=QRMFNS+ΔQPB
QAUX=QRMFNS-QRMFNS-QRMFMC
QXCES=|QAUX| if QAUX<0

RTN

831

ROOM NEEDS MORE HEAT

HOUR UP

OVER-SHOOT (IF ANY) ACCEPTABLE

BACK-UT AND CONTINUE AT REDUCED INTERVAL

QRMFNS=QADTOT

QRMFNS=QRMFNS+ QPD
QAUX=QROOM-QRMFNS-QRMFMC
QXCES=|QAUX| if QAUX<0

RTN

40

QRMFNS=ΔQPB

81

HEAT STORAGE HEAT COLLECTOR

ΔT STOR>0

29 DOES TIME REMAIN

30 STORAGE BELOW MAX TEMP

STOP ACTIVE HEATING

113

QU=ΔQRB+QLOSS
QRMFNS=QRMFNS+QLOSSH
QSTFMC=QU

QRMFNS=QRMFNS+ΔQRB
QAUX=QROOM-QRMFNS-2KAFMC
QXCES=|QAUX| if QAUX<0

RTN

FIGURE A.2 (cont.)

TABLE A.1

Sample of Yearly Simulation Output for an
Average Day in Each Month

Collector Area: 5m x 12m

Storage Volume: 6.8m^2 x 2.5m

Temperatures in °C

Hours are Solar Time

SEPTEMBER

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0- 1	14.45	0.0	0.0	1450.3	0.0	1450.6	0.0	0.0	458.3
1- 2	14.56	0.0	0.0	1409.5	0.0	1448.9	0.0	0.0	456.0
2- 3	14.88	0.0	0.0	1289.7	0.0	1367.2	0.0	0.0	453.7
3- 4	15.39	0.0	0.0	1097.8	0.0	1125.3	0.0	0.0	451.6
4- 5	16.07	0.0	0.0	844.6	0.0	883.1	0.0	0.0	449.8
5- 6	16.07	0.0	0.0	545.6	0.0	561.7	0.0	0.0	448.5
6- 7	17.75	4611.7	837.2	1257.3	837.2	418.6	0.0	1.4	418.7
7- 8	18.65	13438.0	501.3	919.4	501.3	417.8	0.0	0.3	418.1
8- 9	19.53	21446.2	1670.8	591.3	173.9	419.0	1496.9	0.0	417.4
9-10	20.33	27044.2	5315.4	0.0	0.0	424.3	6515.4	0.0	419.1
10-11	21.01	32538.9	8996.0	0.0	0.0	435.8	8996.0	0.0	428.3
11-12	21.52	34917.2	401.7	0.0	0.0	441.7	401.7	0.0	441.7
12-13	21.84	39917.2	532.6	0.0	0.0	441.8	532.6	0.0	441.0
13-14	21.95	32538.9	388.5	0.0	0.0	441.5	389.5	0.0	440.9
14-15	21.84	27944.1	435.1	0.0	0.0	441.6	436.1	0.0	441.1
15-16	21.52	21446.2	0.0	0.0	0.0	440.8	0.0	0.0	441.0
16-17	21.01	13487.9	0.0	0.0	0.0	440.3	0.0	0.0	441.0
17-18	20.33	4611.7	0.0	0.0	0.0	440.3	0.0	0.0	440.3
18-19	19.53	0.0	0.0	591.3	0.0	609.2	0.0	0.0	439.6
19-20	18.65	0.0	0.0	919.4	0.0	990.3	0.0	0.0	438.7
20-21	17.75	0.0	0.0	1257.3	0.0	1293.9	0.0	0.0	437.1
21-22	16.97	0.0	0.0	1585.4	0.0	1596.1	0.0	0.0	435.1
22-23	16.07	0.0	0.0	844.8	0.0	886.9	0.0	0.0	461.4
23-24	15.39	0.0	0.0	1097.8	0.0	1128.9	0.0	0.0	460.0
MONTHLY TOTALS		8096757.0	587668.9	471048.1	45306.5	556531.6	542362.4	48.4	317458.6

QXCSMT= 1.30839E 05   QUQRM = 0.96982   QUQI = 7.25808E-02   QAXQRM= 1.02739E-04   QSLRQR= 0.99990

SEPTEMBER

STORAGE SEGMENT TEMPERATURE AT BEGINNING OF HOUR INDICATED

HOUR					
6- 7	64.771	63.096	62.012	60.570	52.444
7- 8	64.701	63.029	61.947	60.506	52.394
8- 9	64.632	62.962	61.862	60.444	52.344
9-10	61.166	62.745	62.243	61.091	55.789
10-11	62.167	62.150	62.243	61.767	59.184
11-12	55.464	63.319	62.450	62.019	60.665
12-13	65.413	63.252	62.384	61.953	60.622
13-14	55.446	63.252	62.346	61.902	60.599
14-15	65.599	63.289	62.323	61.857	60.504
15-16	55.591	63.325	62.303	61.814	60.588
16-17	65.266	63.501	62.370	61.813	60.669
17-18	65.125	63.433	62.304	61.748	60.605
18-19	65.126	63.365	62.234	61.683	60.542
19-20	55.157	63.353	62.231	61.664	60.140
20-21	65.077	63.334	62.221	61.529	59.400
21-22	55.738	63.308	62.205	61.567	58.657
22-23	54.990	63.277	62.185	61.468	57.653
23-24	54.965	63.261	62.173	61.404	57.102
0- 1	64.034	63.241	62.157	61.317	56.407
1- 2	64.594	63.214	62.134	61.189	55.533
2- 3	64.654	63.188	62.108	61.044	54.679
3- 4	64.416	63.163	62.082	60.894	53.889
4- 5	64.786	63.142	62.057	60.760	53.251
5- 6	64.762	63.126	62.036	60.647	52.760

OCTOBER

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0- 1	7.40	0.0	0.0	4087.7	0.0	4153.3	0.0	0.0	436.7
1- 2	7.54	0.0	0.0	4034.0	0.0	4068.3	0.0	0.0	430.2
2- 3	7.97	0.0	0.0	3875.7	0.0	3903.6	0.0	0.0	423.8
3- 4	8.65	0.0	0.0	3622.2	0.0	3659.2	0.0	0.0	417.7
4- 5	9.54	0.0	0.0	3288.1	0.0	3336.7	0.0	0.0	412.0
5- 6	10.59	0.0	0.0	2893.0	0.0	2935.8	0.0	0.0	406.7
6- 7	11.75	4294.3	0.0	3499.4	0.0	3505.0	0.0	0.0	373.2
7- 8	12.95	12978.4	2733.3	3053.1	2685.4	367.3	47.9	0.9	367.7
8- 9	14.11	20764.4	3847.9	2619.8	2252.6	368.6	1595.3	0.5	367.2
9-10	15.16	27121.7	6552.6	2224.6	1855.5	373.2	4697.1	0.0	369.1
10-11	16.05	31616.9	9425.8	1890.6	1514.7	382.3	7911.2	0.0	375.9
11-12	16.73	33943.8	11351.1	1637.1	1249.4	394.8	10101.7	0.0	387.7
12-13	17.16	33943.8	11680.3	1478.8	1075.9	410.5	10604.4	0.0	402.9
13-14	17.30	31616.9	10231.0	1425.0	1006.2	425.3	9224.8	0.0	418.8
14-15	17.16	27121.6	7212.9	1478.8	1046.2	436.7	6166.7	0.0	432.6
15-16	16.73	20764.4	1286.6	1637.1	1195.5	441.4	91.1	0.2	441.5
16-17	16.05	12978.4	1449.6	1890.6	1449.6	440.8	0.0	0.2	441.0
17-18	15.16	4294.3	61.4	2224.6	61.4	440.3	0.0	0.2	440.3
18-19	14.11	0.0	0.0	2619.8	0.0	2644.4	0.0	1722.9	439.6
19-20	12.95	0.0	0.0	3053.1	0.0	3096.1	0.0	0.0	435.5
20-21	11.75	0.0	0.0	3499.4	0.0	3546.4	0.0	0.0	430.6
21-22	10.59	0.0	0.0	3932.7	0.0	3995.8	0.0	0.0	425.1
22-23	9.54	0.0	0.0	3288.1	0.0	3361.4	0.0	0.0	447.7
23-24	8.65	0.0	0.0	3622.2	0.0	3678.1	0.0	0.0	442.4
MONTHLY TOTALS		8104598.0	2011296.0	2073133.0	476864.5	1561816.0	1534431.0	53435.0	309284.8

QXCSKT= 18984.   OUQRM = 0.96102   QUQI = 0.24817   QAXQRM= 2.57750E-02   QSLRQM= 0.97423

OCTOBER

STORAGE SECTION TEMPERATURE AT BEGINNING OF HOUR INDICATED

HOUR					
6- 7	54.333	63.004	62.426	54.158	39.163
7- 8	54.193	62.993	63.023	53.049	38.023
8- 9	60.910	62.453	60.685	53.602	38.690
9-10	54.510	61.495	60.763	55.747	43.867
10-11	54.134	58.134	60.079	58.357	51.334
11-12	57.172	57.277	58.497	58.741	55.469
12-13	62.172	59.168	58.307	58.411	57.189
13-14	65.466	61.149	59.665	58.777	57.911
14-15	65.625	63.215	61.589	59.860	58.684
15-16	65.030	64.065	63.122	60.243	59.903
16-17	64.772	64.527	63.699	61.333	59.788
17-18	64.733	64.892	63.032	61.256	59.725
18-19	64.804	64.322	62.965	61.204	59.665
19-20	64.462	64.242	62.823	60.860	57.942
20-21	64.400	64.042	62.782	60.509	56.056
21-22	64.857	64.153	62.656	59.998	56.965
22-23	64.637	64.352	62.492	59.511	51.810
23-24	64.636	63.730	62.340	58.911	50.035
24- 1	64.423	63.603	62.160	59.151	48.196
1- 2	64.342	63.477	61.920	57.337	46.245
2- 3	64.365	63.336	61.656	56.501	44.449
3- 4	64.247	63.205	61.357	55.676	42.822
4- 5			61.051	54.896	41.399
5- 6			60.745		40.163

NOVEMBER

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0-1	-0.44	0.0	0.0	7021.8	0.0	4733.2	0.0	2288.5	25.0
1-2	-0.29	0.0	0.0	6962.6	0.0	3657.1	0.0	3305.5	17.6
2-3	-0.18	0.0	0.0	6788.5	0.0	2678.5	0.0	4110.0	11.9
3-4	-0.92	0.0	0.0	6509.6	0.0	1855.1	0.0	4654.6	7.7
4-5	1.91	0.0	0.0	6142.2	0.0	1219.7	0.0	4922.5	4.8
5-6	3.07	0.0	0.0	5707.5	0.0	766.0	0.0	4941.5	2.9
6-7	4.34	2625.7	0.0	6270.6	0.0	-27.1	0.0	6297.7	-27.1
7-8	5.66	9551.5	2337.2	5779.7	2337.2	-27.0	0.0	3469.6	-27.1
8-9	6.53	15761.1	7050.1	5303.0	5330.1	-26.7	1720.0	0.0	-27.1
9-10	6.09	20831.2	10740.4	4868.4	4892.7	-21.8	5847.7	0.0	-24.3
10-11	9.08	24416.3	13140.2	4500.9	4516.1	-10.6	8624.2	0.0	-15.1
11-12	9.82	26272.1	14284.6	4222.0	4223.7	4.0	10060.9	0.0	-1.6
12-13	10.29	26272.1	14161.4	4048.0	4033.9	19.9	10127.6	0.0	14.1
13-14	10.44	24416.3	12844.5	3988.8	3958.9	34.9	8885.6	0.0	29.9
14-15	10.29	20831.1	10435.4	4048.0	4004.2	47.0	6431.2	0.0	43.8
15-16	9.82	15751.1	7137.1	4222.0	4169.3	54.7	2968.8	0.0	53.7
16-17	9.08	9551.5	2955.6	4500.9	2955.6	58.3	0.0	1487.0	58.3
17-18	8.09	2625.6	0.0	4868.4	0.0	4875.9	0.0	0.0	58.2
18-19	6.93	0.0	0.0	5303.0	0.0	5307.3	0.0	0.0	50.6
19-20	5.66	0.0	0.0	5779.7	0.0	5780.3	0.0	0.0	42.3
20-21	4.34	0.0	0.0	6270.6	0.0	6306.0	0.0	0.0	33.2
21-22	3.07	0.0	0.0	6747.2	0.0	5282.6	0.0	1464.7	23.4
22-23	1.91	0.0	0.0	6142.2	0.0	6201.8	0.0	0.0	43.9
23-24	0.92	0.0	0.0	6509.6	0.0	5897.1	0.0	612.5	34.2
MONTHLY TOTALS		5967455.0	2753718.0	3975145.0	1205336.0	1804346.0	1548383.0	970435.8	33248.3

QXCS4T= 4963.7   QUQRM = 0.69149   QUQI = 0.46146   QAXQRM= 0.24413   QSLRQR= 0.75587

NOVEMBER

SURFACE SIGMOND TEMPERATURE AT BEGINNING OF HOUR INDICATED

HOUR				
7 - 8	17.569	17.729	17.577	17.519	17.563
7 - 8	17.657	17.724	17.581	17.523	17.567
8 - 9	17.766	17.776	17.565	17.528	17.511
9 -10	18.022	17.866	17.630	17.646	17.520
10-11	21.035	19.003	17.943	17.635	17.549
11-12	24.772	21.109	18.924	17.994	17.665
12-13	27.132	23.534	20.507	19.856	18.030
13-14	29.662	25.651	22.580	20.220	19.776
14-15	28.107	27.115	24.446	21.920	21.873
15-16	28.371	28.176	26.949	23.321	22.002
16-17	28.925	28.715	26.572	24.243	22.000
17-18	26.172	27.276	26.536	24.311	21.369
18-19	26.503	26.371	25.426	22.414	20.625
19-20	25.816	25.711	24.262	21.633	20.622
20-21	23.094	23.461	23.132	20.959	20.428
21-22	22.353	22.653	22.311	20.622	20.337
22-23	21.516	21.843	21.743	19.928	19.798
23-0	20.665	20.977	20.902	19.245	19.018
0 - 1	19.842	19.265	19.078	18.270	17.709
1 - 2	18.741	18.602	18.450	17.396	17.534
2 - 3	18.342	18.172	18.027	17.686	17.514
4 - 5	17.741	17.991	17.760	17.588	17.514
5 - 6	18.257		17.651	17.541	17.506

DECEMBER

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0- 1	-5.44	0.0	0.0	8891.8	0.0	2953.4	0.0	5938.4	17.3
1- 2	-5.29	0.0	0.0	8832.6	0.0	2464.3	0.0	6368.3	12.7
2- 3	-4.82	0.0	0.0	8658.5	0.0	1908.5	0.0	6750.0	8.9
3- 4	-4.59	0.0	0.0	9379.6	0.0	1374.3	0.0	7005.4	5.9
4- 5	-3.09	0.0	0.0	9012.2	0.0	800.3	0.0	7211.8	3.7
5- 6	-1.33	0.0	0.0	7577.5	0.0	92.9	0.0	7484.6	2.5
6- 7	-0.66	2322.7	0.0	8140.6	0.0	-26.4	0.0	8167.0	-26.5
7- 8	0.66	8877.1	1197.3	7649.7	1197.3	-25.4	0.0	6478.0	-26.5
8- 9	1.93	14753.8	5547.9	7173.0	5547.9	-25.8	0.0	1651.5	-26.4
9-10	3.09	19552.0	9019.7	6738.4	6764.7	-21.0	2255.0	0.0	-26.4
10-11	4.03	22944.9	11377.4	5370.9	6393.7	-12.3	4983.7	0.0	-22.8
11-12	4.62	24701.2	12576.6	6092.0	6107.0	-2.0	6469.5	0.0	-15.0
12-13	5.29	24701.2	12626.2	5918.0	5922.8	7.9	6703.4	0.0	-4.8
13-14	5.44	22944.9	11540.6	5858.8	5853.1	15.5	5687.5	0.0	5.7
14-15	5.29	19552.0	9371.9	5918.0	5903.4	19.9	3468.5	0.0	14.5
15-16	4.82	14753.8	6072.1	6092.0	6072.1	19.9	0.0	0.1	19.9
16-17	4.08	8877.1	1814.9	6370.9	1814.9	19.9	0.0	4536.1	19.9
17-18	3.09	2322.6	0.0	6738.4	0.0	6228.7	0.0	509.7	10.1
18-19	1.93	0.0	0.0	7173.0	0.0	3943.6	0.0	3229.4	4.0
19-20	0.65	0.0	0.0	7649.7	0.0	2086.2	0.0	5563.4	0.7
20-21	-0.66	0.0	0.0	8140.6	0.0	591.2	0.0	7549.4	-0.2
21-22	-1.93	0.0	0.0	8617.2	0.0	-0.2	0.0	8617.4	28.6
22-23	-3.09	0.0	0.0	8012.2	0.0	3845.3	0.0	4166.9	28.6
23-24	-4.08	0.0	0.0	8379.6	0.0	3355.3	0.0	5024.3	22.6
MONTHLY TOTALS		5775395.0	2515510.0	5498925.0	1598889.0	916192.3	916623.6	2984201.0	1486.8

QXCSMT= 345.35   QUQRM = 0.45739   QUQI = 0.43555   QAXQRM= 0.54269   QSLRQR= 0.45731

DECEMBER

STORAGE SEGMENT TEMPERATURE AT BEGINNING OF HOUR INDICATED

JANUARY

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0-1	-6.84	0.0	0.0	9414.0	0.0	2775.1	0.0	6630.9	16.3
1-2	-6.63	0.0	0.0	9358.7	0.0	2312.2	0.0	7046.5	12.0
2-3	-6.26	0.0	0.0	9195.9	0.0	1795.4	0.0	7400.5	8.4
3-4	-5.55	0.0	0.0	8935.2	0.0	1297.6	0.0	7637.5	5.6
4-5	-4.64	0.0	0.0	8591.6	0.0	530.3	0.0	8051.3	3.5
5-6	-3.56	0.0	0.0	8185.1	0.0	86.1	0.0	8099.0	2.7
6-7	-2.36	2560.0	0.0	8779.1	0.0	-26.2	0.0	8805.4	-26.2
7-8	-1.14	9415.5	1104.5	8370.1	1104.5	-26.1	0.0	7241.8	-26.2
8-9	0.06	15562.0	5632.2	7874.4	5632.2	-26.1	0.0	2268.4	-26.2
9-10	1.14	20580.6	9197.9	7468.0	7494.1	-25.8	1703.9	0.0	-26.1
10-11	2.06	24129.3	11644.7	7124.4	7147.8	-22.0	4496.9	0.0	-23.4
11-12	2.76	25956.3	12884.9	6863.6	5880.0	-14.1	6004.9	0.0	-16.4
12-13	3.19	25965.3	12943.0	6700.9	6707.8	-4.5	6235.2	0.0	-6.9
13-14	3.34	24129.3	11832.7	6645.5	6642.7	4.7	5190.0	0.0	2.8
14-15	3.19	20550.6	9574.3	6700.9	6680.9	11.6	2884.4	0.0	10.9
15-16	2.76	15562.0	6125.9	6863.6	6125.9	15.4	0.0	722.4	15.4
16-17	2.06	9415.5	1682.9	7124.4	1682.9	15.4	0.0	5426.1	15.4
17-18	1.14	2560.0	0.0	7468.0	0.0	5893.1	0.0	1574.8	15.4
18-19	0.06	0.0	0.0	7874.4	0.0	3401.5	0.0	4472.9	6.2
19-20	-1.14	0.0	0.0	8320.1	0.0	1533.1	0.0	6787.1	0.8
20-21	-2.36	0.0	0.0	8779.1	0.0	-1.5	0.0	8780.7	-1.6
21-22	-3.56	0.0	0.0	9224.8	0.0	-1.5	0.0	9226.4	-1.6
22-23	-4.64	0.0	0.0	8591.6	0.0	3795.2	0.0	4796.3	27.3
23-24	-5.56	0.0	0.0	8935.2	0.0	3196.0	0.0	5739.1	21.3
MONTHLY TOTALS		6089250.0	2561313.0	5993482.0	1739339.0	821810.8	821976.5	3432621.0	294.6

QXCSMT= 278.01   OUQRM = 0.42730   QUQI = 0.42063   QAXQRM= 0.57273   QSLRQR= 0.42727

JANUARY

STORAGE SEGMENT TEMPERATURE AT BEGINNING OF HOUR INDICATED

FEBRUARY

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0-1	-6.84	0.0	0.0	9414.0	0.0	3184.3	0.0	5229.7	18.5
1-2	-6.63	0.0	0.0	9358.7	0.0	2645.1	0.0	6713.6	13.5
2-3	-6.26	0.0	0.0	9195.9	0.0	2035.5	0.0	7160.5	9.4
3-4	-5.56	0.0	0.0	8935.2	0.0	1457.0	0.0	7478.2	6.2
4-5	-4.64	0.0	0.0	8591.6	0.0	815.5	0.0	7775.1	3.9
5-6	-3.56	0.0	0.0	8185.1	0.0	85.8	0.0	8099.3	2.6
6-7	-2.36	3490.8	0.0	8779.1	0.0	-26.3	0.0	8805.4	-26.3
7-8	-1.14	11105.7	1773.1	8320.1	1773.1	-25.2	0.0	6573.2	-26.3
8-9	0.06	18105.6	6896.0	7874.4	6896.0	-26.2	0.0	1004.7	-26.2
9-10	1.14	23746.7	11005.9	7468.0	7494.2	-25.3	3511.7	0.0	-26.2
10-11	2.06	27735.6	13722.3	7124.4	7145.1	-18.1	6577.2	0.0	-20.7
11-12	2.76	29800.3	15085.4	6863.6	6874.0	-6.8	8211.4	0.0	-10.4
12-13	3.19	27735.6	15098.6	6700.3	6698.4	6.2	8400.3	0.0	2.5
13-14	3.34	23746.7	13785.2	6645.5	6629.9	18.6	7155.4	0.0	15.6
14-15	3.19	18105.6	11219.8	6700.9	6674.1	28.3	4545.7	0.0	26.8
15-16	2.76	11196.7	7395.8	6963.6	6829.8	33.8	566.1	0.0	33.9
16-17	2.06	3490.8	2352.6	7124.4	2357.6	34.7	0.0	4737.1	34.7
17-18	1.14	0.0	0.0	7468.0	0.0	7471.7	0.0	0.0	34.6
18-19	0.06	0.0	0.0	7874.4	0.0	6280.6	0.0	1593.8	23.0
19-20	-1.14	0.0	0.0	8320.1	0.0	4002.4	0.0	4317.8	13.1
20-21	-2.36	0.0	0.0	8779.1	0.0	2295.1	0.0	6484.1	6.9
21-22	-3.56	0.0	0.0	9224.8	0.0	1067.6	0.0	8157.2	3.3
22-23	-4.64	0.0	0.0	8591.6	0.0	4029.5	0.0	4562.1	30.4
23-24	-5.56	0.0	0.0	8935.2	0.0	3604.0	0.0	5331.2	24.1
MONTHLY TOTALS		6386226.0	2753361.0	5413468.0	1662272.0	1091142.0	1091091.0	2660603.0	4677.0

QXCSMT= 538.64   QU2RM = 0.50851   QUQI = 0.43101   QAXORM= 0.49148   QSLRQR= 0.50852

FEBRUARY

AVERAGE SEAWATER TEMPERATURE AT BEGINNING OF HOUR INDICATED

HOUR				
5-7	17.946	17.635	17.538	17.566
7-9	17.950	17.642	17.547	17.510
9-11	17.544	17.646	17.547	17.519
11-13	17.556	17.656	17.551	17.519
13-15	17.646	17.745	17.690	17.535
15-17	18.405	18.159	18.713	17.577
17-19	21.111	19.135	19.075	17.731
19-21	22.225	21.503	20.603	17.668
21-23	22.373	22.130	20.730	18.497
23-1	21.245	23.048	20.707	18.846
1-3	20.462	23.466	20.855	19.106
3-5	20.373	21.750	20.455	19.147
5-7	20.245	20.351	20.405	19.774
7-9	20.462	20.082	20.177	19.773
9-11	20.256	20.216	20.665	20.194
11-13	19.632	20.041	20.211	20.242
13-15	19.376	20.470	20.747	20.260
15-17	18.405	19.301	18.747	18.616
17-19	18.659	18.303	17.633	17.947
19-21	17.965	17.957	17.661	17.690
21-23		17.747	17.576	17.573
23-1		17.648	17.541	17.530
1-3				17.512
3-5				17.506

MARCH

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HP)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0- 1	-1.18	0.0	0.0	7295.7	0.0	7340.3	0.0	0.0	44.9
1- 2	-1.04	0.0	0.0	7244.6	0.0	6884.7	0.0	359.9	33.4
2- 3	-0.64	0.0	0.0	7094.3	0.0	5036.5	0.0	2057.8	22.6
3- 4	0.01	0.0	0.0	6853.4	0.0	3506.7	0.0	3346.8	14.7
4- 5	0.95	0.0	0.0	6536.1	0.0	2326.3	0.0	4209.8	9.2
5- 6	1.86	0.0	0.0	6160.7	0.0	1476.3	0.0	4684.4	5.6
6- 7	2.96	4415.6	0.0	6788.8	0.0	-25.5	0.0	6814.2	-25.5
7- 8	4.09	13026.8	3160.1	6364.8	3160.1	-25.5	0.0	3230.2	-25.5
8- 9	5.19	20747.3	9095.1	5953.2	5978.6	-24.5	3116.5	0.0	-25.5
9-10	6.20	27051.1	13750.3	5577.7	5598.3	-16.7	8152.0	0.0	-20.5
10-11	7.04	31508.6	16732.9	5260.4	5268.2	-1.4	11464.7	0.0	-7.8
11-12	7.59	33615.9	18094.6	5019.6	5000.4	17.8	13085.2	0.0	10.2
12-13	8.09	33815.9	17842.2	4869.2	4838.6	38.3	13003.6	0.0	30.6
13-14	8.23	31508.6	16120.4	4818.1	4767.2	57.5	11353.2	0.0	50.9
14-15	8.09	27051.1	13047.9	4869.2	4800.6	72.9	8247.3	0.0	68.6
15-16	7.69	20747.3	8786.2	5019.6	4938.2	82.7	3848.0	0.0	81.4
16-17	7.04	13026.7	3697.8	5260.4	3697.8	87.2	0.0	0.0	87.3
17-18	6.20	4415.6	0.0	5577.8	0.0	5586.9	0.0	1475.3	87.1
18-19	5.19	0.0	0.0	5953.2	0.0	5993.6	0.0	0.0	78.4
19-20	4.09	0.0	0.0	6364.8	0.0	6371.8	0.0	0.0	69.0
20-21	2.96	0.0	0.0	6788.8	0.0	6795.5	0.0	0.0	59.0
21-22	1.86	0.0	0.0	7200.4	0.0	7246.9	0.0	0.0	48.4
22-23	0.85	0.0	0.0	6536.1	0.0	6581.5	0.0	0.0	65.9
23-24	0.01	0.0	0.0	6853.4	0.0	6860.8	0.0	0.0	55.6
MONTHLY TOTALS		8095036.0	3730236.0	4534059.0	1489774.0	2239952.0	2240462.0	811792.1	25345.8

QXCSMT= 7449.6   QUQRM = 0.82107   QUQI = 0.46081   QAXQRM= 0.17904   QSLRQR= 0.82096

@

MARCH

AVERAGE SECOND TEMPERATURE AT BEGINNING OF HOUR INDICATED

17.035	17.655	17.549	17.506	
17.036	17.555	17.549	17.515	
17.042	17.660	17.549	17.514	
17.037	17.765	17.695	17.522	
18.012	18.366	17.790	17.660	
21.099	19.827	18.404	17.728	
25.227	22.079	19.679	19.427	
30.013	25.617	21.537	21.045	
31.413	26.936	23.641	22.686	
31.422	28.549	25.557	23.935	
30.575	29.605	26.627	23.029	
28.737	29.530	26.817	22.764	
27.604	28.536	25.715	21.331	
27.255	27.372	24.556	21.005	
25.685	26.107	23.468	20.505	
24.606	24.776	22.475	19.377	
23.849	24.428	21.630	18.586	
22.106	23.575	20.936	17.695	
20.705	22.603	20.008	17.575	
19.595	21.445	18.296	17.532	
18.797	19.325	17.891	17.513	
16.266	18.564	17.667		
	18.081	17.587		
	17.807			

APRIL

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0- 1	4.25	0.0	0.0	5267.7	0.0	5284.8	0.0	0.0	140.6
1- 2	4.37	0.0	0.0	5219.3	0.0	5247.3	0.0	0.0	132.3
2- 3	4.76	0.0	0.0	5076.9	0.0	5097.6	0.0	0.0	124.1
3- 4	5.37	0.0	0.0	4848.7	0.0	4874.2	0.0	0.0	116.1
4- 5	6.17	0.0	0.0	4548.1	0.0	4557.7	0.0	0.0	108.5
5- 6	7.12	0.0	0.0	4192.4	0.0	4216.2	0.0	0.0	101.4
6- 7	8.16	4314.2	3237.6	4842.2	3237.6	4855.0	0.0	1147.6	62.8
7- 8	9.24	12131.1	8032.5	4440.5	3995.4	55.2	4137.1	0.0	55.3
8- 9	10.28	19139.6	11664.0	4050.5	3633.5	56.8	8033.6	0.0	55.2
9-10	11.23	24862.0	13975.0	3694.9	3320.4	66.0	10654.6	0.0	61.4
10-11	12.03	28908.4	15085.5	3394.2	3075.7	80.6	12009.8	0.0	73.9
11-12	12.64	31002.8	14915.4	3166.1	2914.6	98.3	12000.7	0.0	90.4
12-13	13.03	31002.9	13420.9	3023.6	2847.6	116.9	10573.3	0.0	109.0
13-14	13.15	28908.4	10609.3	2975.2	2879.7	134.5	7729.6	0.0	127.6
14-15	13.03	24862.0	6765.5	3023.6	3010.3	148.7	3755.2	0.0	144.0
15-16	12.64	19139.6	3390.9	3166.1	3232.8	157.7	158.1	0.0	155.8
16-17	12.03	12131.1	0.0	3394.2	0.0	161.4	0.0	0.0	161.4
17-18	11.23	4314.2	0.0	3694.9	0.0	3713.4	0.0	0.0	161.4
18-19	10.28	0.0	0.0	4050.5	0.0	4065.0	0.0	0.0	155.6
19-20	9.24	0.0	0.0	4440.5	0.0	4464.1	0.0	0.0	149.3
20-21	8.16	0.0	0.0	4842.2	0.0	4848.2	0.0	0.0	142.3
21-22	7.12	0.0	0.0	5232.1	0.0	5236.0	0.0	0.0	134.7
22-23	6.17	0.0	0.0	4548.1	0.0	4568.7	0.0	0.0	155.3
23-24	5.37	0.0	0.0	4848.7	0.0	4876.6	0.0	0.0	148.2
MONTHLY TOTALS		7221476.0	3066602.0	2999437.0	966589.4	2000228.0	2100014.0	41059.8	80507.9

QXCSHT= 8437.7   QUQRM = 1.0196   QUQI = 0.42465   QAXQRM= 1.36892E-02   QSLRQR= 0.98631

APRIL

STORAGE SEGMENT TEMPERATURE AT BEGINNING OF HOUR INDICATED

HOUR				
7	33.663	36.472	26.521	18.934
8	34.531	29.327	25.351	19.268
9	35.511	28.313	25.344	19.249
10	36.146	29.981	27.013	20.482
11	35.435	30.133	26.453	22.421
12	35.608	30.964	29.502	24.522
13	35.719	32.672	30.740	26.424
14	37.233	34.707	32.366	28.113
15	37.145	34.450	34.115	29.714
16	37.062	34.493	35.606	31.247
17	37.223	37.715	36.514	32.765
18	37.473	37.450	36.627	32.886
19	37.253	37.474	34.913	30.153
20	37.216	34.350	35.933	29.573
21	37.123	36.593	34.778	27.673
22	37.720	36.121	33.066	26.148
23	36.743	35.709	33.279	24.744
24	35.744	35.219	32.456	23.744
1	36.725	34.599	31.566	22.665
2	35.395	33.017	30.594	21.692
3	34.262	32.192	29.609	20.404
4	34.374	32.415	28.642	20.251
5		31.641	27.725	19.739
6			23.202	19.335

MAY

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0- 1	11.09	0.0	0.0	2707.7	0.0	2780.6	0.0	0.0	446.6
1- 2	11.21	0.0	0.0	2664.7	0.0	2699.2	0.0	0.0	442.2
2- 3	11.54	0.0	0.0	2538.1	0.0	2539.2	0.0	0.0	438.0
3- 4	12.09	0.0	0.0	2335.2	0.0	2378.9	0.0	0.0	434.0
4- 5	12.90	0.0	0.0	2068.0	0.0	2140.0	0.0	0.0	430.3
5- 6	13.65	0.0	0.0	1751.9	0.0	1821.4	0.0	0.0	426.9
6- 7	14.57	4388.7	1099.3	2445.0	1098.3	391.4	0.0	955.3	391.2
7- 8	15.53	12394.0	1697.4	2087.9	1697.4	390.0	0.0	0.5	390.5
8- 9	16.45	19571.3	1918.1	1741.3	1351.3	390.4	565.8	0.0	389.9
9-10	17.30	25431.6	3862.7	1425.2	1034.9	392.8	2827.8	0.0	390.2
10-11	18.01	25575.4	6905.6	1157.9	763.9	398.7	6141.7	0.0	394.0
11-12	16.56	31720.4	8904.5	955.1	552.1	409.5	8352.4	0.0	403.0
12-13	18.89	31720.4	9261.4	828.5	413.1	421.7	8843.3	0.0	415.4
13-14	19.01	29575.4	7827.6	785.5	355.9	433.8	7470.8	0.0	428.6
14-15	18.89	25431.5	1778.5	928.5	388.9	441.0	1389.6	0.1	439.6
15-16	16.56	19571.3	638.9	955.1	514.0	441.0	124.9	0.3	441.1
16-17	18.01	12393.9	717.3	1157.9	717.3	440.3	0.0	0.2	440.6
17-18	17.30	4388.7	985.2	1425.2	985.2	439.7	0.0	0.0	439.9
18-19	16.45	0.0	0.0	1741.3	0.0	1797.8	0.0	0.0	439.2
19-20	15.53	0.0	0.0	2087.9	0.0	2097.5	0.0	0.0	436.4
20-21	14.57	0.0	0.0	2444.9	0.0	2470.8	0.0	0.0	433.1
21-22	13.65	0.0	0.0	2791.6	0.0	2844.4	0.0	0.0	429.3
22-23	12.80	0.0	0.0	2068.0	0.0	2147.2	0.0	0.0	453.7
23-24	12.09	0.0	0.0	2335.2	0.0	2384.4	0.0	0.0	450.3
MONTHLY TOTALS		7631031.0	1598109.0	1343150.0	315527.4	1014201.3	1282581.0	30641.9	297978.8

QXCSMT= 17221.   QUQRM = 1.1770   QUQI = 0.20942   QAXQRM= 2.28135E-02   QSLRQR= 0.97719

MAY

STORAGE SEGMENT TEMPERATURE IN DEGREES F BEGINNING OF HOUR INDICATED

					Hour
53.160	62.979	61.501	57.453	44.513	6- 7
53.118	62.912	61.434	57.295	44.475	7- 8
53.652	62.345	61.372	57.337	44.497	8- 9
56.290	62.467	61.543	58.191	47.115	9-10
58.724	60.213	61.370	59.763	52.940	10-11
59.357	59.280	60.115	60.223	57.062	11-12
59.564	59.289	59.763	59.025	58.700	12-13
59.447	60.476	59.775	60.043	53.430	13-14
60.118	60.698	62.328	60.078	60.051	14-15
60.502	60.207	62.760	61.275	60.243	15-16
60.511	64.310	60.656	61.429	60.342	16-17
60.502	64.241	60.790	61.365	60.290	17-18
60.273	64.172	62.733	61.301	60.217	18-19
60.235	64.126	62.697	61.735	59.006	19-20
60.155	64.072	62.632	61.127	57.679	20-21
60.157	64.331	62.562	60.741	56.152	21-22
60.111	64.252	62.475	60.564	54.448	22-23
60.135	63.322	62.407	60.426	53.227	23-24
	63.751	62.323	60.172	51.008	24- 1
	63.681	62.713	59.720	51.412	1- 2
	63.611	62.083	59.287	49.023	2- 3
	63.543	61.967	58.345	47.779	3- 4
	63.481	61.837	58.003	46.553	4- 5
		61.710	57.935	45.675	5- 6

JUNE

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0-1	16.09	0.0	0.0	837.7	0.0	1291.1	0.0	837.7	1291.3
1-2	16.21	0.0	0.0	794.7	0.0	1284.4	0.0	794.7	1284.5
2-3	16.54	0.0	0.0	668.1	0.0	1272.8	0.0	668.1	1272.8
3-4	17.09	0.0	0.0	465.2	0.0	1256.7	0.0	465.2	1256.6
4-5	17.80	0.0	0.0	198.0	0.0	1236.4	0.0	198.0	1236.7
5-6	18.65	0.0	0.0	-118.1	0.0	1213.9	0.0	-118.1	1214.0
6-7	19.57	4194.0	0.0	574.9	0.0	1181.1	0.0	574.9	1181.1
7-8	20.53	12630.2	0.0	217.9	0.0	1156.4	0.0	217.9	1156.2
8-9	21.45	20193.9	0.0	-128.7	0.0	1131.4	0.0	-128.7	1131.9
9-10	22.30	26369.6	2763.1	0.0	0.0	1112.6	2763.1	0.0	1109.6
10-11	23.01	30736.6	5869.2	-712.1	0.0	1107.5	5869.2	-712.1	1099.3
11-12	23.56	32997.0	7427.5	-914.9	0.0	1113.9	7427.5	-914.9	1103.1
12-13	23.89	32997.0	7340.9	-1041.5	0.0	1127.3	7340.9	-1041.5	1116.6
13-14	24.01	30736.6	5547.3	-1084.5	0.0	1142.4	5547.3	-1084.5	1134.7
14-15	23.89	26359.6	2309.4	-1041.5	0.0	1154.1	2309.4	-1041.5	1151.9
15-16	23.56	20193.9	0.0	-914.9	0.0	1162.8	0.0	-914.9	1163.1
16-17	23.01	12630.2	0.0	-712.1	0.0	1171.1	0.0	-712.1	1171.2
17-18	22.30	4194.0	0.0	0.0	0.0	1183.1	0.0	0.0	1183.1
18-19	21.45	0.0	0.0	-128.7	0.0	1197.8	0.0	-128.7	1197.8
19-20	20.53	0.0	0.0	217.9	0.0	1214.4	0.0	217.9	1214.2
20-21	19.57	0.0	0.0	574.9	0.0	1231.4	0.0	574.9	1231.2
21-22	18.65	0.0	0.0	921.6	0.0	1246.9	0.0	921.6	1247.5
22-23	17.80	0.0	0.0	198.0	0.0	1261.9	0.0	198.0	1262.0
23-24	17.09	0.0	0.0	465.2	0.0	1273.9	0.0	465.2	1273.6
MONTHLY TOTALS		7627270.0	996172.6	-19887.7	0.0	841692.2	996172.6	-19887.7	840340.1

a

QUJI = 0.13061

JUVE

AVERAGE SEGMENT TEMPERATURE AT BEGINNING OF HOUR INDICATED

	75.740	74.057	73.673	72.793	71.725
	75.693	73.677	73.493	72.606	71.552
	73.311	73.730	73.317	72.434	71.363
	73.665	73.526	73.145	72.255	71.217
	73.242	74.330	73.178	72.701	72.065
	77.772	75.864	74.377	72.029	72.360
	74.656	76.792	74.168	73.332	72.770
	77.551	77.455	75.318	75.116	73.230
	77.002	77.251	76.360	75.009	73.691
	76.655	76.313	76.863	75.045	74.562
	76.243	76.543	76.600	75.772	74.642
	76.431	76.155	76.536	75.527	74.511
	76.621	76.554	76.146	75.241	74.277
	75.743	75.777	75.042	74.656	74.162
	75.043	75.577	75.775	74.475	73.964
	75.243	75.370	75.565	74.650	73.664
	75.233	75.163	75.303	74.500	73.621
	74.435	75.866	75.200	74.312	73.435
	74.243	74.956	75.064	74.117	72.249
	74.551	74.796	74.916	73.924	73.055
	74.461		74.616	73.734	72.976
	74.231	74.607	74.425	73.546	72.684
			74.237	73.361	72.499
					72.318

JULY

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-HR)
0- 1	19.00	0.0	0.0	-248.9	0.0	1307.8	0.0	-248.9	1308.2
1- 2	19.10	0.0	0.0	-286.2	0.0	1301.7	0.0	-286.2	1301.6
2- 3	19.39	0.0	0.0	-395.8	0.0	1291.1	0.0	-395.8	1290.9
3- 4	19.86	0.0	0.0	-571.5	0.0	1275.8	0.0	-571.5	1276.2
4- 5	20.43	0.0	0.0	-802.9	0.0	1258.3	0.0	-802.9	1258.4
5- 6	21.21	0.0	0.0	0.0	0.0	1232.1	0.0	0.0	1238.1
6- 7	22.01	4292.6	0.0	0.0	0.0	1214.4	0.0	0.0	1214.4
7- 8	22.84	12550.7	0.0	-646.4	0.0	1192.2	0.0	-646.4	1192.2
8- 9	23.64	20523.6	0.0	-946.6	0.0	1170.3	0.0	-946.6	1170.5
9-10	24.37	26758.6	2571.7	-1220.4	0.0	1153.1	2571.7	-1220.4	1150.5
10-11	24.93	31218.6	5670.2	-1451.9	0.0	1149.3	5670.2	-1451.9	1141.6
11-12	25.46	33511.7	7218.3	-1627.5	0.0	1156.6	7218.3	-1627.5	1146.2
12-13	25.75	33511.8	7128.7	-1737.2	0.0	1170.1	7128.7	-1737.2	1159.9
13-14	25.85	31218.6	5340.8	-1774.4	0.0	1184.7	5340.8	-1774.4	1177.5
14-15	25.75	26788.6	2113.6	-1737.2	0.0	1195.3	2113.6	-1737.2	1193.4
15-16	25.46	20523.6	0.0	-1627.5	0.0	1202.8	0.0	-1627.5	1202.9
16-17	24.99	12850.6	0.0	-1451.9	0.0	1209.2	0.0	-1451.9	1209.3
17-18	24.37	4292.5	0.0	-1220.4	0.0	1219.2	0.0	-1220.4	1218.9
18-19	23.64	0.0	0.0	-946.6	0.0	1230.6	0.0	-946.6	1231.0
19-20	22.84	0.0	0.0	-646.4	0.0	1244.7	0.0	-646.4	1244.6
20-21	22.01	0.0	0.0	0.0	0.0	1258.3	0.0	0.0	1258.7
21-22	21.21	0.0	0.0	-37.0	0.0	1272.2	0.0	-37.0	1272.2
22-23	20.48	0.0	0.0	-802.9	0.0	1284.2	0.0	-802.9	1284.1
23-24	19.86	0.0	0.0	-571.5	0.0	1293.6	0.0	-571.5	1293.5
MONTHLY TOTALS		8009513.0	945863.6	-643288.9	0.0	909065.9	945863.6	-643288.9	907834.9

QUQI = 0.11809

JULY

STORAGE SEGMENT TEMPERATURE AT BEGINNING OF HOUR INDICATED

AUGUST

HOUR	AMBIENT TEMP (C)	HOURLY INCIDENT HEAT (W-HR)	HOURLY USEFUL HEAT (W-HR)	HOURLY ROOM HEAT NEEDS (W-HR)	HOURLY COLLECTED HEAT TO ROOM (W-HR)	HOURLY STORAGE HEAT TO SURR (W-HR)	HOURLY COLLECTED HEAT TO STORAGE (W-HR)	HOURLY AUXILIARY HEAT TO ROOM (W-HR)	HOURLY STORAGE LOSS TO SURR (W-FR)
0- 1	18.54	0.0	0.0	-78.1	0.0	1297.5	0.0	-78.1	1297.5
1- 2	18.63	0.0	0.0	-111.9	0.0	1291.1	0.0	-111.9	1291.3
2- 3	18.90	0.0	0.0	-211.3	0.0	1281.1	0.0	-211.3	1281.1
3- 4	19.32	0.0	0.0	-370.7	0.0	1267.5	0.0	-370.7	1267.5
4- 5	19.88	0.0	0.0	-580.7	0.0	1250.8	0.0	-580.7	1250.9
5- 6	20.55	0.0	0.0	-829.1	0.0	1232.2	0.0	-829.1	1232.1
6- 7	21.27	442.6	0.0	-61.7	0.0	1212.5	0.0	-61.7	1212.5
7- 8	22.03	12662.9	2670.9	0.0	0.0	1191.7	2670.9	0.0	1191.9
8- 9	22.75	20033.1	5499.4	0.0	0.0	1171.9	5499.4	0.0	1171.9
9-10	23.42	26050.9	6901.7	-863.0	0.0	1155.2	6901.7	-863.0	1153.4
10-11	23.98	30306.1	6812.6	-1072.9	0.0	1153.5	6812.6	-1072.9	1146.1
11-12	24.40	32508.7	5174.0	-1232.3	0.0	1160.9	5174.0	-1232.3	1151.1
12-13	24.67	32508.7	2211.6	-1331.8	0.0	1174.0	2211.6	-1331.8	1154.3
13-14	24.76	30306.1	0.0	-1365.6	0.0	1189.0	0.0	-1365.6	1181.0
14-15	24.67	26050.9	0.0	-1331.8	0.0	1198.2	0.0	-1331.8	1196.2
15-16	24.40	20033.1	0.0	-1232.3	0.0	1205.6	0.0	-1232.3	1205.4
16-17	23.98	12662.9	0.0	-1072.9	0.0	1210.6	0.0	-1072.9	1210.8
17-18	23.42	4442.5	0.0	-863.0	0.0	1219.2	0.0	-863.0	1219.2
18-19	22.75	0.0	0.0	0.0	0.0	1230.0	0.0	0.0	1229.8
19-20	22.03	0.0	0.0	0.0	0.0	1241.4	0.0	0.0	1241.7
20-21	21.27	0.0	0.0	-61.7	0.0	1254.2	0.0	-61.7	1254.1
21-22	20.55	0.0	0.0	210.7	0.0	1266.1	0.0	210.7	1266.0
22-23	19.88	0.0	0.0	-580.7	0.0	1276.1	0.0	-580.7	1276.4
23-24	19.32	0.0	0.0	-370.7	0.0	1284.7	0.0	-370.7	1284.6
MONTHLY TOTALS		7812256.0	903664.7	-415753.1	0.0	913031.4	903664.7	-415753.1	911867.1

@ QUCI = 0.11567

@ NRSEGS=   7

@ TOTSEG= 7.0000   NRSEGS=   7

AUGUST

STORAGE SEGMENT TEMPERATURE AT BEGINNING OF HOUR INDICATED

HOUR				
5			76.757	75.045	74.978
7			76.575	75.764	74.600
8			76.392	75.595	74.625
9			76.214	75.410	74.453
10			76.231	75.730	75.061
11			75.415	75.072	75.450
12			77.145	76.355	75.769
13			78.104	77.073	76.242
14			79.120	78.368	75.935
15			79.550	78.735	77.711
16			79.407	78.555	77.541
17			79.223	78.374	77.363
18			79.052	78.192	77.194
19			78.463	78.008	77.068
20			78.473	77.222	76.822
21			78.281	77.635	76.637
22			78.087	77.345	76.444
23			77.892	77.255	76.244
24			77.605	77.052	76.075
1			77.405	76.578	75.894
2			77.305	76.483	75.604
3			77.112	76.294	75.406
4			76.923	76.107	75.314
5					75.135

COMPUTER NOMENCLATURE

FOR FIGURE A.2

AREAC	surface area of collector
DEGDAY	heat load of dwelling; (W-HR/°C-HR)
ΔT	difference in temperature between storage bed surroundings and average temperature in bed
ΔT_{stor}	change in temperature of storage due to heating bed with the collector
ΔQPB	heat transferred from storage while storage is idle (convective losses)
ΔQRB	heat transeferred to storage from collector
DLTIME	time, in seconds, remaining in any given hour for performing any of the several modes of heat transfer possible in this simulation
DLTIMH	one hour in seconds
IFLAG	when equal to 1, indicates the collector is presently heating storage after having heated the dwelling; used as an internal logic signal only
QADINT	heat transferred in an interval (either 60 sec or 5 sec) when storage used to heat dwelling
QADTOT	heat transferred while heating room from storage
QAUX	auxiliary heat required by dwelling
QAXQRM	monthly ratio of auxiliary heat supplied to room needs
QI	solar radiation incident upon collector
QLOSSH	Total amount of heat lost from storage to room while storage being heated by collector (QLOSS refers to the amount lost in either 60 sec or 5 sec)

QRATIO	ratio of energy supplied from storage in small interval to the room needs in that interval
QRMFMC	heat transferred to the dwelling from collector
QRMFMS	heat transferred to the dwelling from storage
QROOM	hourly room energy requirement
QROOM1	hourly room energy requirement accounting for the uncontrolled storage loss
QSLRQR	monthly ratio of solar energy supplied to room needs
QSTFMC	heat transferred to storage from collector
QSUBLS	uncontrolled convective losses from storage
QU	hourly thermal energy extracted from the collector by the system = QRMFMC + QSTFMC
QUQI	ratio of QU to QI
QUQRM	ratio of QU to QROOM
QXCES	the hourly amount of energy supplied to the residence for which there is no need (convective losses or "overshoot" from storage)
QXCSMT	monthly total of QXCES
SI	flux of solar radiation incident upon the collector surface area
SURFAR	surface area of storage bed through which convective loss takes place
TAMB	ambient temperature
TAVCHK	maximum average storage temperature allowed
TREF	average value of allowable room temperature range
TSAVG	average instantaneous temperature in storage bed

LISTING OF
COMPUTER
SIMULATION

TABLE A.3

```
USER=RAMSAY    662  21451    JOINT COMPUTER FACILITY, MIT

      REAL KT, KTKD, LENGTH, KINS, N, KAIR, MU, MDOT
      DIMENSION  KT(12), H(12), XDAYS(12), TSUBBS(33), AVDAT(12),
     1           TSUBFS(33), TIME(24), TSBBSH(33), XTAMB(24),
     2           XQI(24), XQU(24), XQROOM(24), XQRMFC(24), XQSBLS(24),
     3           XQRMFS(24), XQSTFC(24), XQADX(24), AVNIT(12),
     4           XQAUX(24), XQXCES(24), XQI(24), XQU(24), XQROOM(24),
     5           XQSBLS(24), XQRMFC(24), XQRMFS(24), XQSTFC(24),
     6           XQXCES(24)
      READ (8,10) TIME, H, KT, XDAYS, AVDAT, AVNIT
      ALF60D=0.9346
      BETA=50.0
      CVRNBR=2.
      DEGDAY=374.0
      DLTIMH=3600.0
      DSCHGT=60.0
      DUST=0.02
      EMISGL=0.88
      EMISPL=0.95
      EPS1=EMISPL
      EPS2=EMISPL
      GAMMA=0.0
      KAIR=0.029
      KINS=0.043
      MDOT=1.2
      MU=1.912E-5
      PBLDIA=0.0508
      PHI=40.77
      PI=3.141593
      PLTSPC=0.01
      DO 500 KK=1,3
      IF (KK .EQ. 1)    AREAXS=6.0
      IF (KK .EQ. 1)    LENGTH=2.0
      IF (KK .EQ. 2)    AREAXS=6.8
```

USER=RAMSAY   662 21451   JOINT COMPUTER FACILITY, MIT

```
IF (KK .EQ. 2)  LFNGTH=2.5
IF (KK .EQ. 3)  AREAXS=7.5
IF (KK .EQ. 3)  LENGTH=3.2
PLLONG=5.0
PLWDTH=12.0
REFNDX=1.526
RHOGR=0.2
RHOPBL=2400.0
SHADE=0.03
SIGMA=5.6697E-8
SPHTFL=1.012
SPHTPB=0.837
TASH3A=62.78
TASHRM=35.0
THKINS=0.076
THTA6C=60.*PI/180.
TRDWH=21.11
TRDWL=19.44
TRNWH=18.33
TRNWL=16.57
TRDSH=22.78
TRDSL=21.11
TRNSH=22.78
TRNSL=18.33
VOIDR=0.3
VWIND=5.0
AREAC=PLWDTH*PLLONG
BTARDN=BETA*PI/180.
FLOARA=PLTSPC*PLWDTH
G=MDOT/AREAC
GMMRDN=GAMMA*PI/180.
H1=(0.0158*(MDOT*PLTSPC*2.0/(FLOARA*MU))**0.8*KAIR)/(PLTSPC*2.0)
H2=H1
```

```
USER=RAMSAY   662 21451    JOINT COMPUTER FACILITY, MIT

      HR=4.0*SIGMA*(340.0**3)/(1./EPS1+1./EPS2-1.0)
      HV=650.0*((MDOT/AREAXS))/(PBIDIA))**0.7)
      SEGDET=0.0
17    SEGDET=SEGDET+1.0
      HALMCS=(HV*AREAXS*LENGTH*1.E-3)/(MDOT*SPHTFL*SEGDET)
      DELTAU=((RHOPBL*AREAXS*LENGTH/SEGDET)*(1.0-VOIDR)*SPHTPB)/((MDOT*
     1      SPHTFL)*(1.0-EXP(-(HALMCS))))
      IF (DELTAU .GT. 3600.0)  GO TO 17
      TOTSEG=SEGDET-1.0
      HALMCN=(HV*AREAXS*LENGTH*1.E-3)/(MDOT*SPHTFL*TOTSEG)
      NRSEGS=IFIX(SEGDET-1.0)
      PUT NRSEGS
      DO 6 I1=1,NRSEGS
      TSURBS(I1)=62.78
6     CONTINUE
      NRSEG1=NRSEGS+1
      TSUBFS(1)=20.27
      TSUBFS(NRSEG1)=62.78
      PUT TOTSEG, NRSEGS
      HWIND=5.7+3.8*VWIND
      PHIRDN=PHI*PI/180.
      RHOLAN=RHOPBL*AREAXS*LENGTH/TOTSEG
      RSUBPF=1.0/(AREAC*H1)
      SURFAR=(LENGTH*PI*(2.0*SQRT(AREAXS/PI))+2.0*AREAXS)/TOTSEG
      THTA25=ASIN(SIN(THTA60)/RFRNDX)
      RHO60D=.5*(((SIN(THTA26-THTA60))**2/(SIN(THTA26+THTA60))**2)+((
     1      TAN(THTA26-THTA60))/(1.+(2.*CVRNBR-1.)*RHO60D)
      TAU60D=(1.-RHO50D)/(1.+(2.*CVRNBR-1.)*RHO60D)
      TAUALD=(TAU60D*ALF60D)/(1.-(1.-ALF60D)*RH060D)

      IFLAG1=1
```

C

C C

```
USER=RAMSAY   662  21451      JOINT COMPUTER FACILITY, MIT

        DO  1 II=1,12
        DO 84 KI=1,24
        YQI(KI)=0.0
        YQU(KI)=0.0
        YQRQOM(KI)=0.0
        YQSBLS(KI)=0.0
        YQRMFC(KI)=0.0
        YQRMFS(KI)=0.0
        YQSTFC(KI)=0.0
        YQAUX(KI)=0.0
        YQXCES(KI)=0.0
   84   CONTINUE
        IIFLAG=0
   19   IIFLAG=IIFLAG+1
        I=II+3
        IF (II .GE. 5)   I=II-4
        IF (IIFLAG .LE. 8)   GO TO 601
        GO TO (64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75), I
   64   WRITE (5,1001)
        GO TO 76
   65   WRITE (5,1002)
        GO TO 76
   66   WRITE (5,1003)
        GO TO 76
   67   WRITE (5,1004)
        GO TO 76
   68   WRITE (5,1005)
        GO TO 76
   69   WRITE (5,1006)
        GO TO 76
   70   WRITE (5,1007)
        GO TO 76
   71   WRITE (5,1008)
```

```
USER=RAMSAY    662 21451     JOINT COMPUTER FACILITY, MIT


72                  GO TO 76
                    WRITE (5,1009)
73                  GO TO 76
                    WRITE (5,1010)
74                  GO TO 76
                    WRITE (5,1011)
75                  GO TO 76
                    WRITE (5,1012)
76          WRITE (5,1027)
601         KTKD=.795-.84*KT(I)
            N=INT(-16.3+30.5*FLOAT(I)+0.5)
            DELTA=23.45*SIN((360.*(284.+N)/365.)*PI/180.)
            DLTRDN=DELTA*PI/180.
            COSWS=-(TAN(PHIRDN)*TAN(DLTRDN))
            TAVCHK=TASHRA
            IF (II .GE. 10)   TAVCHK=TASHRM
C
            DO 2 JJ=1,24
            J=JJ+6
            IF (JJ .GE. 19)   J=JJ-18
C
            IHOURB=J-1
            IHOURS=J
            TAMB=(AVDAT(I)+AVNIT(I))/2.0+(((AVDAT(I)-AVNIT(I))/(2.0*0.7071))*
           1      SIN((PI/13.0)*TIME(J)-7.0*PI/13.0))
            IF (IFLAG1 .EQ. 1)  TPLATC=TAMB+10.0
            IFLAG1=0
            TAMBK=TAMB+273.15
            QXCES=0.0
            QRMFMS=C.0
            IFLAG=0
            DLTIME=DLTIMB
            TREF=TRDWH
```

```
USER=RAMSAY   662  21451    JOINT COMPUTER FACILITY, MIT

      TRMIN=TRDWL
      IF (JJ .GE. 17)  TREF=TRNWH
      IF (JJ .GE. 17)  TRMIN=TRNWL
      IF (II .LE.9)  GO TO 60
      TREF=TRDSL
      TRMIN=TRDSH
      IF (JJ .GE. 17)  TREF=TRNSL
      IF (JJ .GE. 17)  TRMIN=TRNSH
   60 TSURR=(TREF+TRMIN)/2.0
      TSURS=TSURR
      IF (II .GE. 10)  TSURS=TAMB
   61 QROOM=DEGDAY*(TREF-TAMB)
      IF (TAMB .GE. TRDSH)  GO TO 608
      IF (TAMB .GE. TSURR)  QROOM=0.0
  608 USUBLS=0.283
      IF (II .GE. 10)  USUBLS=0.6
      QSUBLS=0.0
  609 DO 63 I5=1,NRSEGS
      QSUBLS=USUBLS*SURFAR*(TSUBBS(I5)-TSURS)+QSUBLS
   63 CONTINUE
   62 QROOM1=QROOM-QSUBLS
      W=(12.-TIME(J))*15.0*PI/180.0
      COSW=COS(W)
      COSTHT=COS(DLTRDN)*COS(W)*(COS(GMMRDN)*SIN(BTARDN)*SIN(PHIRDN)+
     1 COS(PHIRDN)*COS(BTARDN))+SIN(GMMRDN)*SIN(BTARDN)*COS(DLTR
     2 DN)*SIN(W)+SIN(DLTRDN)*(SIN(PHIRDN)*COS(BTARDN)-COS(GMMRDN
     3 )*COS(PHIRDN)*SIN(BTARDN))
      SNALFA=SIN(DLTRDN)*SIN(PHIRDN)+COS(DLTRDN)*COS(PHIRDN)*COS(W)
      PSUBB=COSTHT/SNALFA
      RSUBD=PI/24.*(COS(W)-COSWS)/(SIN(ACOS(COSWS))-ACOS(COSWS)*COSWS)
      SI=RSUBD*H(I)*1.0E4*((RSUBB*(1.0-KTKD))+(0.5*(1.0+COS(BTARDN))*
     1 KTKD)+(0.5*(1.0-COS(BTARDN))*RHOGR))/3.6
      IF (SI .GT. 0.0)  GO TO 18
```

```
          SI=0.0
          QI=0.0
          QU=0.0
          QSTFMC=0.0
          QRMFMC=C.0
      IF (II .GE. 1C) GO TO 40
      IF (QROOM1 .GT. 0.0) GO TO 121
          QRMFMS=0.0
          GO TO 40
18    QI=SI*AREAC
      THETAT=ACOS(COSTHT)
      THTA2T=ASIN(SIN(THETAT)/RFRNDX)
      RHOTH=.5*((SIN(THTA2T-THETAT))**2/(SIN(THTA2T+THETAT))**2)+((
     1 TAN(THTA2T-THETAT))**2/(TAN(THTA2T+THETAT))**2))
      ALFTHT=1.0-20.03/((100.03-THETAT)**1.3)
      TAUTHT=(1.-RHOTHT)/(1.+(2.*CVRNBR-1.)*RHOTHT)
      TAUALB=(TAUTHT*ALFTHT)/(1.-(1.-ALFTHT)*RHO60D)
      S=(TAUALB*RSUBD*H(I)*1.0E4*RSUBB*(1.0-KTKD)+TAUALD*RSUBD*H(I))*
     1 *1.0E4/2.0*(1.0+COS(BTARDN))*KTKD+(1.0-COS(BTARDN))*RHOGR))*
     2 (1.0-SHADE)*(1.0-DUST)/3.6
      IF (II .GE. 10)  GO TO 77
      IF (QROOM1 .GT. 0.0) GO TO 824
77    TSSUM=0.0
      DO 82 IK=1,NKSEGS
      TSSUM=TSSUM+TSUBBS(IK)
82    CONTINUE
      TSAVG=TSSUM/TOTSEG
      IF (TSAVG .LT. TAVCHK)  GO TO 880
          QU=0.0
          QRMFMC=C.0
          QSTFMC=0.0
          QRMFMS=0.0
          IFLAG=0
```

```
USER=RAMSAY    662 21451    JOINT COMPUTER FACILITY, MIT

           GO TO 40
850        TSBFI=TSUBBS(NRSEGS)
           QRMFMC=0.0
           QRMFMS=0.0
           GO TO 825
824        TSBFI=TSURR
825,       IFLAG=0
C
111        TPLATI=TPLATC
           TPLTIK=TPLATC+273.15
           IF (QI .NE. 0.0) GO TO 827
           TPLATI=TAMB+10.0
           TPLTIK=TPLATI+273.15
827        SMALF=(1.0-0.04*HWIND+5.0E-4*(HWIND)**2)*(1.0+0.058*CVRNBR)
           UT45DG=(1./(CVRNBR/((344./TPLTIK)*((TPLTIK-TAMBK)/(CVRNBR+SMALF)
          1     )**.31)+1./HWIND))+((SIGMA*(TPLTIK+TAMBK)*(TPLTIK**2+TAMBK
          2     **2))/(((1./(EMISPL+.0425*CVRNBR*(1.-EMISPL)))+((2.*CVRNBR
          3     +SMALF-1.)/EMISGL)-CVRNBR))
           UTBETA=UT45DG*(1.-(BETA-45.)*(.00259-.00144*EMISPL))
           USUBT=UTBETA
           USUBB=KINS/THKINS
           USUBL=USUBT+USUBB
           FPRIME=1./(1.+(USUBL/(H1+1./(1./H2+1./HR))))
           USBLJ=0.001*USUBL
           FSUBR=(G*SPHTEL/USBLJ)*(1.-EXP(-(USBLJ*FPRIME)/(G*SPHTFL)))
           QUAC=FSUBR*(S-USUBL*(TSBFI-TAMB))
           TSBFM=TSBFI+(QUAC/(USUBL*FSUBR))*(1.-FSUBR/FPRIME)
           QU=QUAC*AREAC
           TPLATC=TSBFM+QU*RSUBPF
           IF ( ABS(TPLATC-TPLATI) .GT. 1.0)     GO TO 111
           IF (IFLAG .EQ. 1) GO TO 771
           IF (II .GE. 10) GO TO 55
           IF (QROOM1 .GT. 0.0) GO TO 32
```

```
55    IF (QU .GT. 0.0)  GO TO 81
      QU=0.0
      QSTEMC=0.0
      GO TO 40
32    IF (QU .GT. 0.0)  GO TO 411
      QU=0.0
      QSTEMC=0.0
      QRMEMC=0.0
      GO TO 121
C
81    TSBEQ=(QU*0.001)/(MDOT*SPHTFL)+TSBFI
      IF (CLTIME .GE. 5.0)  GO TO 87
      QU=QROOM1
      QSTEMC=0.0
      IFLAG=0
      GO TO 11
87    IF (IFLAG .NE. 1)  GO TO 381
      IF (QU .GT. 0.0)  GO TO 192
      QSTEMC=0.0
      IFLAG=0
      QU=QROOM1
      GO TO 11
881   IF (IFLAG .IE. 8)  GO TO 192
      WRITE (5,1019)
      WRITE (5,1021) IHOURE, IHOURE
      WRITE (5,101) (TSUBBS(L3),L3=1,NRSEGS)
102   SUMINT=0.0
      DSCHGT=60.0
      IFLAG6=0
      IFLAG7=0
      QPBZ=0.0
      QLOSSH=0.0
113   TSUBFS(1)=TSBFSI
```

USER=RAMSAY   662 21451   JOINT COMPUTER FACILITY, MIT

```
      DO 3 K=1,NRSEGS
      TSUBFS(K+1)=(TSUBFS(K)-TSUBBS(K))*EXP(-(HALHCV))+TSUBBS(K)
3     CONTINUE
      TSSUM=0.0
      DO 79 IK=1,NRSEGS
      TSSUM=TSSUM+TSUBBS(IK)
79    CONTINUE
      TSAV4=TSSUM/TOTSEG
      QPBA=(RHOLAN*TOTSEG*SPHTPB*(1.0-VOIDR)*TSAVH)/3.6
      IF (IFLAG7 .EQ. 1) GO TO 103
      QP31=QPBA
      IFLAG7=1
103   DO 4 L=1,NRSEGS
      TSBBSH(L)=((MDOT*SPHTFL*(TSUBFS(L)-TSUBES(L+1))-USUBLS*0.001*
     1    SURFAR*(TSUBBS(L)-TSURS))*DSCHGT)/(RHOLAN*(1.0-VOIDR)
     2    *SFHTPB)+TSUBBS(L)
4     CONTINUE
      TSSUM=0.0
      DO 80 IK=1,NRSEGS
      TSSUM=TSSUM+TSBBSH(IK)
80    CONTINUE
      TSAVG=TSSUM/TOTSEG
      IF ((TSAVG-TSAVH) .GE. (0.0005*DSCHGT/60.0) )   GO TO 29
      DLTCHK=DLTIME-SUMINT
      GO TO 48
29    SUMINT=SUMINT+DSCHGT
      DLTCHK=DLTIME-SUMINT
      IF (DLTCHK .GE. 0.0)   GO TO 30
      IF (IFLAG6 .EQ. 0)   GO TO 28
      DLTCHK=DLTCHK+DSCHGT
      GO TO 48
28    DLTCHK=DLTCHK+DSCHGT
      SUMINT=SUMINT-DSCHGT
```

```
USER=RAMSAY  662 21451    JOINT COMPUTER FACILITY, MIT

       DSCHGT=5.0
       IFLAG6=1
       GO TO 113
30     DO 31 IK=1,NRSEGS
       TSUBBS(IK)=TSBBSH(IK)
31     CONTINUE
       QFBZ=(RHOLAN*TOTSEG*SPHTPB*(1.0-VOIDR)*TSAVG)/3.6
       QLOSS=0.0
       DO 201 I5=1,NRSEGS
       QLOSS=USUBLS*SURFAR*(TSUBBS(I5)-TSURS)*DSCHGT/3600.0+QLOSS
201    CONTINUE
       QLOSSH=QLOSS+QLOSSH
       IF (DLTCHK .EQ. 0.0) GO TO 48
       IF (TSAVG .LT. TAVCHK)    GO TO 113
48     QU=(QPBZ-QPB1)+QLOSSH
       IF ((TSAVG-TSAVH) .LT. (0.0005*DSCHGT/60.0))    QU=(QPBA-QPB1)+
      1 QLOSSH
       QRMFMS=QRMFMS+QLOSSH
       QSTFMC=QU
       IF (IFLAG .EQ. 1)  QU=QSTFMC+QROOM1
       IFLAG=0
       IF (DLTCHK .LE. 0.0)   DLTCHK=0.0
       DLTIME=DLTCHK
       DSCHGT=6.0
       GO TO 11
50     XTAMB(J)=TAMB
       XQI(J)=QI
       XQU(J)=QU
       XQROOM(J)=QROOM
       XQSBLS(J)=QSUBLS
       XQRMFC(J)=QRMFMC
       XQRMFS(J)=QRMFMS
       XQSTFC(J)=QSTFMC
```

```
      YQAUX(J)=QAUX
      XQXCES(J)=QXCES
      YQI(J)=QI+YQI(J)
      YQU(J)=QU+YQU(J)
      YQROOM(J)=QROOM+YQROOM(J)
      YQSBLS(J)=QSUBLS+YQSBLS(J)
      YQRMFC(J)=QRMFMC+YQRMFC(J)
      YQRMFS(J)=QRMFMS+YQRMFS(J)
      YQSTFC(J)=QSTFMC+YQSTFC(J)
      YQAUX(J)=QAUX+YQAUX(J)
      YQXCES(J)=QXCES+YQXCES(J)
      CONTINUE
      IF (IIFLAG .LE. 8)   GO TO 19
      QIM=0.0
      QUM=0.0
      QRMM=0.0
      QSBLSM=0.0
      QRFMCM=C.0
      QRFMSM=0.0
      QSFMCM=0.0
      QAUXM=0.0
      QXCESM=0.0
      QI5=0.0
      QU5=0.0
      QRM5=0.0
      QSBLS5=0.0
      QRFMC5=0.0
      QRFMS5=0.0
      QSFMC5=0.C
      QAUX5=0.0
      QXCES5=0.0
      DO 1030 J8=1,24
      QIM=XQI(J8)+QIM
```
   2

```
      QUM=XQU(J8)+QUM
      QRMM=XQROOM(J8)+QRMM
      QSBLSM=XQSBLS(J8)+QSBLSM
      QRFMCM=XQRMFC(J8)+QRFMCM
      QRFMSM=YQRMFS(J8)+QRFMSM
      QSFMCM=XQSTFC(J8)+QSFMCM
      QAUXM=XQAUX(J8)+QAUXM
      QXCESM=XQXCES(J8)+QXCESM
      QI5=Y2I(J9)+QI5
      QU5=Y2U(J8)+QU5
      QRM5=YQROOM(J8)+QRM5
      QSBLS5=YQSBLS(J8)+QSBLS5
      QRFMC5=YQRMFC(J8)+QRFMC5
      QRFMS5=YQRMFS(J8)+QRFMS5
      QSFMC5=YQSTFC(J8)+QSFMC5
      QAUX5=YQAUX(J8)+QAUX5
      QXCES5=YQXCES(J8)+QXCES5
1030  CONTINUE
      QIMT=(XDAYS(I)-9.0)*QIM+QI5
      QUMT=(XDAYS(I)-9.0)*QUM+QU5
      QRMMT=(XDAYS(I)-9.0)*QRMM+QRM5
      QBLSMT=(XDAYS(I)-9.0)*QSBLSM+QSBLS5
      QRFCMT=(XDAYS(I)-9.0)*QRFMCM+QRFMC5
      QRFSMT=(XDAYS(I)-9.0)*QRFMSM+QRFMS5
      QSFCMT=(XDAYS(I)-9.0)*QSFMCM+QSFMC5
      QAUXMT=(XDAYS(I)-9.0)*QAUXM+QAUX5
      QXCSMT=QXCES5+(XDAYS(I)-9.0)*QXCESM
      QUQRM=(QUMT-QXCSMT)/QRMMT
      QUQI=QUMT/QIMT
      QAXQRM=QAUXMT/QRMMT
      QSLRQR=1.0-QAXQRM
      GO TO (164,165,166,167,168,169,170,171,172,173,174,175),I
            WRITE (5,1001)
164
```

```
USER=RAMSAY   652  21451       JOINT COMPUTER FACILITY, MIT

165             GO TO 176
                WRITE (5,1002)
165             GO TO 176
                WRITE (5,1003)
                GO TO 176
167             WRITE (5,1004)
                GO TO 176
168             WRITE (5,1005)
                GO TO 176
169             WRITE (5,1006)
                GO TO 176
170             WRITE (5,1007)
                GO TO 176
171             WRITE (5,1008)
                GO TO 176
172             WRITE (5,1009)
                GO TO 176
173             WRITE (5,1010)
                GO TO 176
174             WRITE (5,1011)
                GO TO 176
175             WRITE (5,1012)
176             WRITE (5,1014)
                WRITE (5,1015)
                WRITE (5,1016)
                WRITE (5,1017)
                WRITE (5,1018)

        DO 1020 J5=1,24
        IHOURB=J5-1
        IHOURE=J5         WRITE (5,1019)
                          WRITE (5,1021)   IHOURB, IHOURE
        WRITE(5,1022) XTAMB(J5), XQI(J5), XQU(J5), XQROOM(J5),
```

```
USER=RAMSAY   662 21451    JOINT COMPUTER FACILITY, MIT

     1                    XQRMFC(J5), XQRMFS(J5), XQSTFC(J5), XQAUX(J5),
     2                    XQSBLS(J5)
1020 CONTINUE
     WRITE (5,1023)
     WRITE (5,1024)
     WRITE (5,1025)  QIMT, QUMT, QRMMT, QRFCMT, QRFSMT, QSFCMT, QAUXMT,
     1               QBLSMT
     IF (II .LE. 9) PUT QXCSMT,QUQRM, QUQI, QAXQRM, QSLRQR
     IF (II .GT. 9) PUT QUQI
   1 CONTINUE
 500 CONTINUE
     STOP
C
C    COLLECTOR HAS SUPPLIED THE ROOM NEEDS IN FULL WITH POTENTIALLY
C    SOME ENERGY LEFT FOR STORAGE
 771 TSSUM=0.0
     DO 83 IK=1,NRSEGS
     TSSUM=TSSUM+TSUBBS(IK)
  83 CONTINUE
     TSAVG=TSSUM/TOTSEG
     IF (TSAVG .LT. TAVCHK)   GO TO 81
     QU=QROOM1
     QSTEMC=0.0
     IFLAG=0
     GO TO 11
C
C    NO DIRECT COLLECTOR HEAT AVAILABLE FOR THE ROOMS' NEEDS SO
C    SEE IF STORAGE CAN SUPPLY THE ENERGY REQUIRED
 121 DLTIME=DLTIMH
     TSSUM=0.0
     DO 91 IK=1,NRSEGS
```

```
USER=RAMSAY   662 21451    JOINT COMPUTER FACILITY, MIT

      TSSUM=TSSUM+TSUBBS(IK)
91    CONTINUE
      TSAVG=TSSUM/TOTSEG
      IF (TSAVG .LE. TSURS)   GO TO 40
      IF (IIFLAG .LE. 8)  GO TO 122
      WRITE (5,1019)
      WRITE (5,1021) IHOURE,IHOURE
      WRITE (5,101) (TSUBBS(L3),L3=1,NRSEGS)
122   QADTOT=0.0
      SUMINT=0.0
      IFLAG=0
      QPBI=0.0
      DSCHGT=60.0
      DO 8 I3=1,NRSEGS
      QPBI=RHOLAN*SPHTPB*(1.0-VOIDR)*TSUBBS(I3)+QPBI
8     CONTINUE
      IFLAGS=C
      IFLAGG=0
      IFLAGH=0
123   TSUBFS(NRSEG1)=TSURR
      DO 13 K1=1,NRSEGS
      K=NRSEG1-K1
      TSUBFS(K)=(TSUBFS(K+1)-TSUBBS(K))*EXP(-(HALMCN))+TSUBBS(K)
13    CONTINUE
      DO 14 L1=1,NRSEGS
      L=NRSEG1-L1
      TSBBSH(L)=((MDOT*SPHTFL*(TSUBFS(L+1)-TSUBFS(L))-USUBLS*0.001*
     1       SURFAR*(TSUBBS(L)-TSURS))*DSCHGT)/(RHOLAN*(1.0-VOIDR)
     2       *SPHTPB)+TSUBBS(L)
14    CONTINUE
      QPBF=0.0
      DO 9 I4=1,NRSEGS
      QPBF=RHOLAN*SPHTPB*(1.0-VOIDR)*TSBBSH(I4)+QPBF
```

```
USER=RAMSAY  662 21451   JOINT COMPUTER FACILITY, MIT

9     CONTINUE
      QADINT=QPBI-QPBF
605   IF (QADINT .GT. 0.0)   GO TO 830
      QRMFMS=0.0
      GO TO 11
830   IF (IFLAGG .EQ. 3)     GO TO 836
      IF (IFLAGG .EQ. 2)     GO TO 835
      QRM2M=(QROOM*3.6)/(DLTIME/60.0)
      QRATIO=QADINT/QRM2M
      IF (QRATIO .GT. 0.10)   GO TO 831
      QRMFMS=QADTOT/3.6
      DLTIME=(DLTIME-SUMINT)
      DLTIMA=((QROOM-QADTOT/3.6)/QSUBLS)*DLTIMH
      IF (DLTIMA .GT. DLTIME)   GO TO 11
      DLTIME=DLTIMA
      GO TO 11
831   QATOT1=QADTOT
835   IF (IFLAGG .EQ. 3)   QADTOT=QATOT1
835   QADTOT=QADINT+QADTOT
839   CCHK=2ROOM*3.6-QADTOT
      IF (QCHK .GT. 0.0)     GO TO 841
      IF (IFLAGG .EQ. 2)     GO TO 841
      CCHK1=ABS(QCHK/(QROOM*3.6))
      IF (QCHK1 .LE. 0.01)   IFLAGH=1
      IF (QCHK1 .LE. 0.01)   GO TO 841
      DSCHGT=5.0
      IFLAGG=3
      IF (IFLAGS .EQ. 1)   IFLAGH=1
      IF (IFLAGS .EQ. 1)   GO TO 841
      IFLAGS=1
      GO TO 123
841   DO 5 I6=1,NRSEGS
      TSUBBS(I6)=TSBBSH(I6)
```

```
USER=RAMSAY  662 21451    JOINT COMPUTER FACILITY, MIT

5      CONTINUE
       QPBI=QPBF
       SUMINT=SUMINT+DSCHGT
       IF (IFLAGH .EQ. 1)  GO TO 843
       IF (IFLAGG .EQ. 3)  IFLAGG=2
       IF (SUMINT .LT. 3600.0)  GO TO 832
       QRMFMS=QADTOT/3.6
       DSCHGT=60.0
       DLTIME=0.0
       GO TO 11
832    IF (QCHK .GT. 0.0)  GO TO 123
843    DSCHGT=60.0
       QRMFMS=QADTOT/3.6
       DLTIME=0.0
       GO TO 11
C
C      COLLECTOR HAS SUPPLIED ENERGY TO THE ROOM, WAS IT ENOUGH?
411    IF ((QROOM1-QU) .LT. 0.0)  GO TO 820
       QSTFMC=0.0
       QRMFMC=QU
       QRMFMS=0.0
       GO TO 40
820    QRMFMS=0.0
       QRMFMC=QROOM1
       TSBFI=TSUBBS(NRSEGS)
       DLTIME=(QROOM1/QU)*DLTIMH
       IFLAG=1
C
C
40     IF (IFLAG .LE. 8)  GO TO 11
       WRITE (5,1019)
       WRITE (5,1021) IHOURB, IHOURE
       WRITE(5,101) (TSUBBS(L3),L3=1,NRSEGS)
```

```
USER=RAMSAY   662  21451      JOINT COMPUTER FACILITY, MIT

11    QPBS=0.0
      DO 15 I3=1,NRSEGS
      QPBS=RHOLAN*SPHTPB*(1.0-VOIDR)*TSUBBS(I3)+QPBS
15    CONTINUE
      DO 12 L=1,NRSEGS
      TSUBBS(L)=(-(USUBLS*0.001*SURFAR*(TSUBBS(L)-TSURS))*
     1          DLTIME)/(RHOLAN*(1.0-VOIDR)*SPHTPB)+TSUBBS(L)
12    CONTINUE
      QPBE=0.0
      DO 16 I3=1,NRSEGS
      QPBE=RHOLAN*SPHTPB*(1.0-VOIDR)*TSUBBS(I3)+QPBE
16    CONTINUE
      QRMFMS=QRMFMS+(QPBS-QPBE)/3.6
      QAUX=QROOM
      IF (II .GE. 10) GO TO 95
      IF (IFLAG .EQ. 1) GO TO 95
      QAUX=QROOM-QRMFMS-QRMEMC
      IF (QAUX .GE. 0.0) GO TO 95
      QXCES=ABS(QAUX)
      QAUX=0.0
95    IF (IFLAG .EQ. 1) DLTIME=(DLTIMH-DLTIME)
      IF (IFLAG .EQ. 1) GO TO 111
      GO TO 50
C
C
C
10    FORMAT(12F5.0)
101   FORMAT (1H+,(14X,10F10.3))
1001  FORMAT (1H1,T52,'JANUARY'/)
1002  FORMAT (1H1,T52,'FEBRUARY'/)
1003  FORMAT (1H1,T52,'MARCH'/)
1004  FORMAT (1H1,T52,'APRIL'/)
1005  FORMAT (1H1,T52,'MAY'/)
```

```
USER=RAMSAY   662 21451   JOINT COMPUTER FACILITY, MIT

1006 FORMAT (1H1,T52,'JUNE'/)
1007 FORMAT (1H1,T52,'JULY'/)
1008 FORMAT (1H1,T52,'AUGUST'/)
1009 FORMAT (1H1,T52,'SEPTEMBER'/)
1010 FORMAT (1H1,T52,'OCTOBER'/)
1011 FORMAT (1H1,T52,'NOVEMBER'/)
1012 FORMAT (1H1,T52,'DECEMBER'/)
1014 FORMAT (1H0,T53,'HOURLY',T64,'HOURLY',T76,'HOURLY',T88,'HOURLY',
    1 T100,'HOURLY',T113,'HOURLY')
1015 FORMAT (1H ,T27,'HOURLY',T40,'HOURLY',T54,'ROOM',T63,'COLLECTED',
    1 T76,'STORAGE',T87,'COLLECTED',T99,'AUXILIARY',
    2 T112,'STORAGE')
1016 FORMAT (1H ,T15,'AMBIENT',T26,'INCIDENT',T40,'USEFUL',T54,'HEAT',
    1 T64,'HEAT TO',T76,'HEAT TO',T88,'HEAT TO',T100,'HEAT TO',
    2 T114,'LOSS')
1017 FORMAT (1H ,T16,'TEMP',T28,'HEAT',T41,'HEAT',T53,'NEEDS',T65,
    1 'ROOM',T77,'SURR',T88,'STORAGE',T101,'ROOM',
    2 T113,'TO SURR')
1018 FORMAT (1H ,T7,'HOUR',T17,'(C)',T27,'(W-HR)',T40,'(W-HR)',T53,
    1 '(W-HR)',T64,'(W-HR)',T76,'(W-HR)',T88,'(W-HR)',T100,
    2 '(W-HR)',T113,'(W-HR)'/)
1019 FORMAT (1H ,T8,'-')
1021 FORMAT (1H+,T6,I2,T9,I2)
1022 FORMAT (1H+,T16,F5.2,T26,F7.1,T40,F7.1,T52,F7.1,T64,F7.1,T76,
    1 F7.1,T88,F7.1,T100,F7.1,T112,F7.1)
1023 FORMAT (1H0,T6,'MONTHLY')
1024 FORMAT (1H ,T6,'TOTALS')
1025 FORMAT (1H+,T24,F10.1,T37,F10.1,T49,F10.1,T61,F10.1,T73,F10.1,
    1 T85,F10.1,T97,F10.1,T109,F10.1//)
1027 FORMAT (1H0,T7,'HOUR',T25,'STORAGE SEGMENT TEMPERATURE AT BEGINNI
    1NG OF HOUR INDICATED'/)
  20 CONTINUE
     END

PROGRAM *MAIN* HAS    NO ERRORS
```

REFERENCES

1.   J. A. Duffie and W. A. Beckman, <u>Solar Energy Thermal Processes</u>, John Wiley and Sons, Inc., New York (1974).

2.   S. A. Mumma and W. C. Marvin, "A Method of Simulating the Performance of a Pebble Bed Thermal Energy Storage and Recovery System", ASME Paper, 76-HT-73.

3.   F. Kreith, <u>Principles of Heat Transfer</u>, International Textbook Company, Scranton, PA, (1965), 2nd ed.

4.   L. W. Butz et. al., "Simulation of a Solar Heating and Cooling System", Solar Energy, Vol. 16, pp. 129-136, (1974).

5.   B. Y. H. Liu and R. C. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation", Solar Energy, <u>4</u>, (3), pp. 1-9, (1960).

6.   J. D. Felske, "The Effect of Off-South Orientation on the Performance of Flat-Plate Solar Collectors", to appear in Solar Energy.

7.   B. Anderson and M. Roidan, <u>The Solar Home Book</u>, Cheshire Books, Harrisville, N.H., (1976).

8.   C. Strock and R. L. Koral, <u>Handbook of Air-Conditioning, Heating and Ventilating</u>, Industrial Press, Inc., New York, 1965, 7-115, 122.